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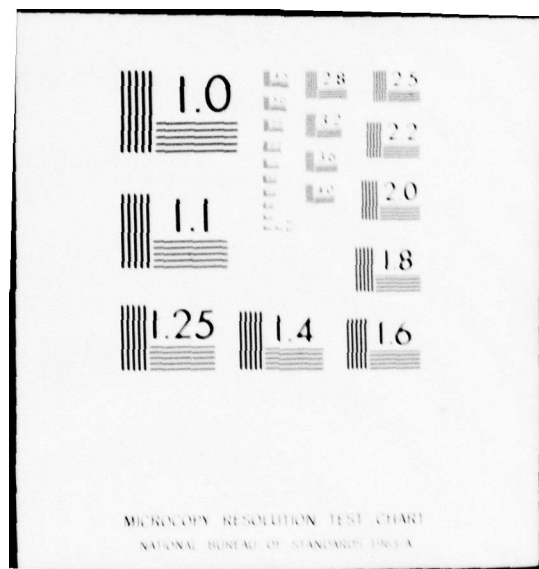
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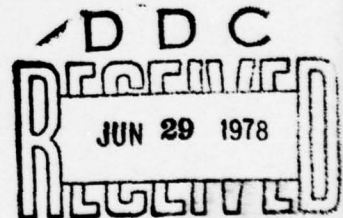
PROCEEDINGS OF A WORKSHOP ON WEAR CONTROL TO ACHIEVE PRODUCT DURABILITY

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ANALYTICAL REWORK/SERVICE LIFE PROJECT OFFICE

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PA 18974

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**PROCEEDINGS OF A WORKSHOP ON
WEAR CONTROL TO ACHIEVE
PRODUCT DURABILITY.**

23-25 February 1976. A

10 EDITED BY

MARTIN J. DEVINE

ANALYTICAL REWORK/SERVICE LIFE PROJECT OFFICE

NAVAL AIR DEVELOPMENT CENTER
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PREFACE

The workshop on "Wear Control to Achieve Product Durability" was held under the auspices of the Office of Technology Assessment (OTA), U. S. Congress. It is but one element in analyzing the broad Assessment on Materials Conservation in the manufacture and use of products that OTA is undertaking at the request of the U. S. Senate Committee on Commerce. The information obtained at the workshop by OTA will be incorporated in its full assessment report to Congress.

The staff of the ARP/SLP Project Office of the Naval Air Development Center participated in the conference planning and are currently engaged in an active wear control program for naval aircraft, with interest in the defining of additional research required in: the life-limiting technology; the economics of wear and durability; the enumeration of maintenance practices of the airlines; the discussions of how increased wear resistance can be achieved; and the listing of the critical problem areas to be addressed. The workshop provided valuable data in these areas and permission was requested from the Office of Technology Assessment to publish the proceedings to assist the staff and to provide information to the engineering community engaged in wear control programs.

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No. 1	Automobile and Automobile Spare Parts	F. F. Ling, Rensselaer Polytechnic Institute
No. 2	Naval Aircraft Structures, Materials and Components	A. J. Koury, Naval Air Systems Command
No. 3	Aircraft Propulsion Systems and Components	P. M. Ku, Southwest Research Institute
No. 4	Metal-Cutting Machinery and Tools	V. Tipnis, Metcut Research Associates
No. 5	Railroad Rolling Stock	E. Rabinowicz, Massachusetts Institute of Technology
No. 6	Construction Equipment	C. L. Kepner, Caterpillar Tractor Company

SUMMARY

A. BACKGROUND

The Office of Technology Assessment, U. S. Congress, is analyzing the potential for materials conservation in the manufacturing and use of products. This assessment will determine at which stages in the materials cycle, materials can be conserved and the potential economic and other impacts of such conservation.

One possible strategy for conservation would be to increase product life through improved corrosion, wear, and fracture control. To explore the conservation potential of increased product life, a workshop was held in Washington, D. C. on the 23rd, 24th, and 25th of February 1976. This document presents the proceedings of that workshop. (See Table A for Agenda.)

Wear control was chosen as an example of a technology to increase product durability. Experts from the field of wear along with representatives from industry discussed the status of wear control technology and its application in the design and maintenance of a range of products (railroad equipment, automobiles, aircraft propulsion, Naval aircraft structures, metal cutting machinery and tools, and heavy construction equipment).

The questions specifically explored were whether product life could be extended by improved wear control and what would be the cost and other consequences of such extension. These questions were explored from various viewpoints: (1) the status of technology to support increases in durability, (2) economic considerations, (3) current policies and programs, and (4) the methodology and information available.

The fact that only a few products were studied limits the conclusions; however, these products are sufficiently representative of a cross section of industry so that the question of product durability could, indeed, be qualitatively explored.

B. FINDINGS

1. Methodology of Economic Appraisal

A large amount of economic data was presented at the workshop establishing that the real cost of wear can be evaluated for a range of products and/or industries. Such information is essential to judge the need for and the significance of new technology.

No standard techniques for acquiring the real costs of wear are available. It is not apparent that a standard technique would suffice; each product might require its own separate analysis.

Standard methodologies, however, are available for economic appraisals and these could be applied to wear, corrosion or any other degradation process. Some such procedures are: (1) National Academy of Corrosion Engineer (NACE) standards for corrosion economies, and (2) Life Cycle Costing.

2. Wear Costs and Consequences

It is clear from information provided during the presentations and seminars of the workshop that (1) data on the cost of wear in several different product areas are available, and (2) that cost appraisal standards or techniques have been developed for this purpose. As expected, the greater part of this information is available from government sources. However, further contacts with representatives from other product sectors are expected to yield additional cost data.

At the workshop examples of specific cost data were presented. These data, if shown to be general, would in themselves provide strong economic incentives for improved product durability and therefore, for increased materials conservation. It is recommended that such data be collected; however, it should also include the cost of other product deterioration technologies such as corrosion, fatigue, contamination, etc. A major source of such data would be the military which retains computerized malfunction maintenance records. Some examples of specific cost data discussed at the workshop include:

- Data on Wear Costs in Naval Aircraft. Data provided on the wear costs in Naval aircraft show that the scheduled maintenance for wear for one

aircraft amounted to \$67 per flight hour; unscheduled maintenance \$140 per flight hour and overhaul \$36.87 per flight hour. Thus, the total cost of wear is \$243.87 per flight hour. This can be compared with the cost of fuel of \$376 per flight hour. Data was also provided on the life cycle costing of Naval aircraft tires. The Navy uses 20,500 tires/year at a cost of \$3.48 per landing for a total yearly cost of \$1,853,200.

- Data on Wear Costs of Diesel Engines. Data provided on the diesel engine maintenance and repair for 20 ships (120 engines) indicated that wear costs were \$38.92 per ship per hour. Fuel costs were \$75.00 per ship hour.
- Data on Wear Costs of Tools. The purchased cost of high speed steel tools (USA) was \$470 million per year; carbide tools \$435 million per year. It was also learned at the workshop that the best estimates of the cost of wear came from users rather than manufacturers of products. The relationship of these costs to manufacturing design decisions was not defined. However, it is not unfair to generalize knowing the above facts that where responsibility is divided between the user and the manufacturers the chief concern of the latter is marketability, with durability being an indirect consideration.

It is clear from the data presented that ignorance as to the wear status costs a significant amount not only from the resultant necessity to overdesign but also from the discard of components. Another important factor regarding wear costs brought forth at the workshop was that few product areas use life cycle costing; and those areas which do use it employ it only at certain stages of their decisionmaking. Also, there is little agreement as to how the appropriate interest rate should be calculated in order to compare different development and procurement plans from the present worth point of view. Present high rates of interest tilt decisions to labor intensive rather than capital intensive projects, with a resulting loss in concern for product durability and hence wear control. The possibilities of technological obsolescence further aggravate the problem. Those responsible for development and procurement are frequently career people who will move on and whose current responsibility is to keep down capital costs, -- not to assure succeeding low cost maintenance programs.

Thus, the above findings, which are but representative of the material that was covered during the workshop, all point to the fact that wear considerations cannot be isolated from the other considerations that go into the design of consumer products.

Wear control simply does not appear to be a primary goal anywhere. Since responsibility for wear control changes hands as the product changes hands during its life cycle, life cycle costing will not be used. The heart of the analysis of wear and wear programs, or the lack of them, lies in the understanding of the objective functions of the producers and the consumers as well as the constraints under which they operate.

3. State of the Technology

It was pointed out at the workshop that tribology, the branch of science concerned chiefly with improvements in wear control for greater product durability, has not received sufficient attention in U.S. academic, industrial, and government institutions; however, the benefits of increased emphasis have not been defined sufficiently by the scientists involved. Further research in the field of wear could result in improved techniques to control damage resulting from sources such as contamination, vibration, misalignment, etc. Thus, the most pressing need is for a centralized source of information on wear control technology which can be effectively used in product design.

At the same time, however, the U.S. is not currently technologically limited for increasing product durability since many newly developed techniques are now currently used by industry. Implementation of this technology in design and maintenance varies from one product to another and one industry to another and is generally limited depending on many other factors including cost effectiveness.

At present, several professional and technical societies sponsor activities which contribute to and facilitate efforts to control wear. Some examples of these societies are as follows:

- American Society of Lubrication Engineers (ASLE) documentation of Wear and Failure Costs;
- American Society for Testing Materials (ASTM) Committee G-2 erosion and wear;
- Mechanical Failure Prevention Group (MFPG) sponsored by the National Bureau of Standards; and
- American Society of Mechanical Engineers (ASME) Lubrication Division and Research Committee on Lubrication.

Existing technology is shared by various manufacturers or industries by communication with each other through these societies.

It was also noted that support programs oriented toward tribology and wear control are sponsored by the National Science Foundation, the Advanced Research Projects Agency of the Department of Defense, the Office of Naval Research, the National Bureau of Standards and the National Aeronautics and Space Administration.

4. Product Durability

Concise definitions of product durability are not available; however, it relates both to the maximum life achieved and the ability of the product to survive both normal and abnormal usage. High product durability appears desirable from the point of view of reliability and materials conservation; however, in practice this is achieved usually at a higher purchase price. Secondly, longer life products may have a tendency to reduce the application of technical innovations.

A definition of optimal durability was not established during the workshop on wear reduction. However, optimal durability is a function of the relationship between the discounted present value of the benefits to society from having the product provide services in its primary function for the time period, and the present value of the full social costs to society of keeping the product in its primary use for the same period of time.

The conclusions of this workshop indicate that considerable improvement in the durability of some products can be achieved if desired. The question which ultimately must be answered is whether increased durability is worth the added costs to the consumer and whether it can be effectively achieved. Product durability is the prerogative of the consumer. It is available if he wants and demands it.

During the workshop several different actions were discussed which could lead to improved durability.

- Industries wherein close-working relationships exist between manufacturer and user, e. g., the Bell System and the heavy construction equipment industry, could provide an active feedback system yielding improved durability of products.

- Inspection requirements and inspection frequency may be utilized to achieve increased product useful life, e.g., based on data from Sweden, and a comparison of states in the U.S., with and without periodic motor vehicle inspection (PMVI), median car life was shown to be extended as a result of PMVI programs.
- At the workshop, active and productive product-durability programs were reported by the Navy Department. These programs, which have designated the Analytical-Rework and Service-Life Programs, are concerned with: (1) impacting life-cycle cost for reducing the cost of aircraft maintenance; (2) application of new technology to aircraft repair-rework aimed at increasing service life and improving performance/safety/quality; (3) conducting the optimum strategy for a more efficient application of materials and processes generated under the Analytical Rework Program (ARP) including methodology for increased utilization of the improved technology during initial manufacture; and (4) component and product durability can be increased through the application of the rapid and precise nondestructive inspection techniques (with the minimum disassembly of components) currently available.

Product life, however, is often not limited by product durability. For example, many products are removed from service which still have some remaining useful life. Among the reasons for early product retirement are the: (1) cost of operation, or repair, (2) productivity or functionality, (3) aesthetics, (4) accidents, (5) physical loss, and (6) style preferences. Nevertheless, the extent to which useful product life can be extended without increased product durability is now known. The primary factors which can affect useful product life are: (1) use, (2) environment, (3) maintenance, (4) procedures, (5) personnel qualifications, (6) inherent durability, (7) design, (8) manufacturing process, and (9) material characteristics.

In addition, product durability is only one approach to materials conservation. Due consideration should be given to other approaches. At this workshop, materials wastage in manufacturing was frequently cited as one means of achieving materials conservation and should be investigated.

5. Capital and Labor

From the manufacturer's point of view there are many restraints in the development of a product: performance, safety, development cost, schedule, energy consumption,

maintenance costs, first costs, appearance, styling, and durability. These restraints must be balanced in such a way as to find widespread consumer acceptance. Where durability has a high value to the consumer, that attribute will be accentuated in the product. Even without this demand, the manufacturer has compelling reasons for maintaining high durability standards. First and foremost, a good service record for durability helps to insure that the customer will return. This is particularly true for industrial consumers who maintain detailed maintenance records and perform component evaluations.

The manufacturers in general cannot design for a given product life. However, they do know and keep records of service problems (warranty or otherwise) and strive to eliminate these. Where there is a close working relationship between the manufacturer and the user, more success and greater durability result. However, the manufacturer is limited in this regard since he seldom has information on the life of a product or a component based upon the service condition in which it operates. Thus, it can be concluded that the acquisition and distribution of such data would provide a necessary base to initiate the engineering development actions for achieving increased product durability.

The results of this workshop suggest that it is primarily the consumer who determines product durability. First of all, in a free market system, products reflect consumer demands. Secondly, evidence presented at the workshop suggests that many failures are service related and that product durability is often a function of the kind of usage and maintenance it receives rather than its design related deficiencies. Market surveys have shown that product durability is very high on the list of customer wants. However, consumers are generally not willing to pay more for increased durability and often when given the choice, they select the lower cost, less durable items (e.g., power tools are often made in different quality lines; even professionals often select lower cost quality). It was further pointed out at the workshop that even sophisticated corporate "buy" decisions of capital equipment are based upon maximizing the immediate cash flow (net present value computation) to the company. Thus, longer life at increased cost

achieved by greater durability will not be sufficient justification for purchase. The incentive to buy must be lower operating or maintenance costs since these directly influence cash flow.

Thus it seems clear, based upon the conclusions of this workshop, that one point of action for increased durability is the consumer, and two areas of appropriate investigation concern maintenance cost reductions and improved durability at equal cost. Programs which identify and correct service related malfunctions, for example the Navy's Analytical Rework Program, should be encouraged since they achieve the above mentioned goals as well as provide reciprocal information to the manufacturer.

Another incentive for the consumer would be the further acquisition of cost data. At this workshop, wear costs were shown to be surprisingly high in a variety of product areas. The same can undoubtedly be said for corrosion, fatigue, and other durability factors. If consumers realized these costs, they might be prompted to take remedial action. It was also pointed out at the workshop that there are acceptable techniques for both assessing durability (wear) costs and in determining how changes in durability would result in system cost savings (cost modeling, economic system analysis) for a number of products.

6. The Life Cycle

Product life is not a clear concept. As an individual product reaches the end of its useful life (as determined by its owner), it is not necessarily scrapped. A product may be reconditioned or rebuilt. Or, when a product is finally considered unuseable, it may be used as a spare part for a similar model. Thus, it is possible to recycle parts as well as materials. It was also learned at the workshop that scrapped products and components could not be considered waste. For example, the majority of workshop participants felt that for those products considered the recycling of materials reached 80 to 90 percent. Thus, while recycling can sometimes result in a combination of materials having different properties, it cannot be considered waste. Furthermore, scrapped products often find value as completely different products.

It should also be noted that the workshop participants expressed one area of concern regarding product life. It was reported that inventories for spare parts often reach a high of 20 to 1. Such an excess in inventory could cause severe economic loss. It was decided that this subject should receive careful consideration in the final assessment on materials conservation.

7. Materials Wastage

It was also found at the workshop that except for spare parts, wastage due to poor product durability seemed small for those products considered. Those products that do not enter the spare parts inventory are often recycled. And, as the supply of material decreases, one would expect more use of spares and more recycling. It was felt by the workshop participants that specific areas of possible wastage should be identified and corrections should be made when possible.

8. Significance for Research

Although this workshop was called to explore the questions of wear, product durability and materials conservation, certain implications for research become obvious when that work is taken in its broadest context. A great proportion of the research undertaken in this country has been related to innovation; that is, finding new ways to accomplish a stated objective. Composite materials are a good example of this type of research. Much less attention has been devoted to disciplines such as wear, mechanical failures, corrosion, fatigue, etc., which affect our knowledge of such factors.

It is clear from the results of this workshop that the wearing of materials produces significant costs in the overall materials cycle. And even more particularly, wear degrades performance so that much of the original value of the product is lost. An emphasis on wear research, particularly those studies which emphasize predictive capability, would be desirable. This emphasis need not be limited only to wear but to all life limiting technologies. Product durability and life prediction are basically the same concept and increased durability will not be attainable without better concepts of component life.

Improved knowledge of component life and the factors which affect it would not only lead to improved durability but allow tradeoff decisions to be made relative to such

factors as materials conservation, life cycle costs, reimbursement for defective products, maintenance costs, net value, and depreciation. At the present time, these are largely guesses.

Life prediction need not be a priori. Diagnostic techniques such as those being used on Naval aircraft should be further developed. Estimates of product life remaining allow "use" decisions to be made which result in longer life and improved utilization. Research emphasis on this subject could lead to considerable improvements in materials utilization.

A greater priority could be given to research that extends product life. That is,

- (1) Improved research and knowledge on what malfunctions actually limit product service life.
- (2) Increased research on those technologies responsible for life determination such as wear, fatigue, etc.
- (3) Increased support of research which allows estimates or predictions to be made of product and component life.
- (4) Expanded research on the subject of diagnostic instrumentation which will allow residual life estimates to be made.

TABLE A

AGENDA

WORKSHOP ON WEAR REDUCTION

Sponsored by the
Office of Technology Assessment
U.S. Congress
Washington, D. C.

23-25 February 1976

Theme: Materials Conservation - Improved Product Durability
by the Application of Wear-Control Technology

Morning Session, Monday 23 February 1976 -- Chairman -- Dr. Elio Passaglia

Opening Remarks - Purpose	M. J. Devine Office of Technology Assessment
Welcome	Emilio Q. Daddario, Director Office of Technology Assessment
Materials Program Overview	A. E. Paladino Office of Technology Assessment
Workshop Background	E. Passaglia National Bureau of Standards

Session A-1

Wear Technology	M. Peterson Wear Sciences
Incentives for Longer Product Life	W. Flanagan Center for Policy Alternatives Massachusetts Institute of Technology
Manufacturing Technology for Materials Conservation	R. Matt Aerojet General

TABLE A (Continued)

Economic Factors in Product Durability	C.H. Madden/R.S. Landry Chamber of Commerce of the United States
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Technology for Estimating Product Durability	J. John IRT Corporation
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Financial and Taxation Implication of Equipment Replacement	P. Lerman Fairleigh-Dickinson
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Session Chairman: Dr. J.B. Wachtman, Jr.

Safety Aspects of Improved Product Durability	H. Azzam Interrad Corporation
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Automobile Durability	D. Barrett Ford Motor Company
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Economic Impact of Tribology (U.K. Experience)	D. Scott National Engineering Laboratory/ Wear Publications
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Improved Product Durability Navy Program	A. Koury Naval Air Systems Command
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Bell Systems Wear Control Program	G. Kitchen Bell Laboratories
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Life-Cycle Costing	T. Brennan Naval Air Development Center
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National Science Foundation Tribology Program	M. Gaus National Science Foundation
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Advanced-Research-Projects Agency Wear Program	E. Van Rueth/R. Miller Advanced Research Projects Agency, Office of Naval Research
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Maintenance Improvements Within the Airlines	T. Matteson United Airlines
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TABLE A (Continued)

Session A-2 (Evening)

ASME Wear Control Handbook	W. Winer Georgia Institute of Technology
ASLE Replacement Costs Survey	R. L. Johnson Rensselaer Polytechnic Institute
ASTM Wear Program	K. C. Ludema University of Michigan
MFPG - Wear Control	E. Klaus Pennsylvania State University

Session B

Seminars

1. Automobiles/Automobile Spare Parts
2. Naval Aircraft Structures/Materials/Components
3. Aircraft/Aircraft Propulsion Systems
4. Metalcutting Machinery and Tools
5. Railroad Rolling Stock
6. Construction Equipment
 - a. Track-Laying Tractors
 - b. Rubber-Tired Earth Moving Equipment

PART ONE: WORKSHOP SUMMARY

Part one of the proceedings contains two chapters. Chapter I presents background material to the workshop, and Chapter II presents the Chairmen's Reports for the six seminars held on wear-control technology in different product areas.

CHAPTER I

INTRODUCTION

Of the many strategies that may exist for materials conservation through reduced wastage, one that is often suggested is increasing product lifetime. Products are lost to service for a variety of reasons. These may be classified as follows:

- Immediate loss. In this case there are included products which are lost to service immediately upon use, the most familiar example being the beverage can. Some of these are recycled after use; others are not.
- Catastrophic loss. Here there is included loss of products to service by such natural disasters as earthquakes and tornadoes, and such man caused disasters as fires and accidents. The material in many such products is recycled.
- Irretrievable loss. Here there are included such losses as ship sinkings, and lead in ammunition. The material from such losses cannot be recycled with any available technology.
- Reversion loss. This may be defined as the conversion of a material during the use of a product into a form which can no longer be recovered. Examples are the rubber lost from a tire during its use (presumably lost as gaseous products or particulate matter) and the reversion of a metal to its oxide during corrosion. In the latter case some of the metal can be recovered.
- Obsolescence. This is one of the major reasons for loss to service. It may be defined as loss of a product which can still perform the function it was designed to perform as well as when it was first made but is replaced because a new product can perform it more economically.
- Wear out. This may be defined as loss to service because a product can no longer carry out its function, and its economic value has decreased to the point where repair is not undertaken. Wear out is thus essentially an economic consideration, but the necessity for having to make this decision is caused by a degradative process. Corrosion and wear are two of the most important causes of wear out.

In consideration of the above factors an assessment approach was formulated to include the possibilities for materials conservation by increasing the durability of products through the control of corrosion and wear process. Wear and corrosion were combined because they are two of the most important processes for products made of

metals. It was also recognized that for both corrosion and wear, control can be affected at two stages: during design and manufacture, and during maintenance. Control of corrosion and wear at these two stages can lead to quite different policy options.

To explore the conservation potential of increased product life a workshop was planned to provide an information forum on the availability of data for the quantification of wear technology. The data derived from the workshop will help to define the state of technology including economic appraisals, technology transfer, wear control programs and materials impact prior to further pursuit of the assessment.

The assessment of materials conservation focuses primarily on the manufacturing and use phases of the material cycle; namely, those phases of the cycle primarily concerned with materials utilization, and where high potential exists for conservation. The scope will be limited to a selected list of materials and several representative product sectors. These are to be ascertained in the assessment and may include, for example, copper, chromium, and nickel as they are used in consumer durables, industrial equipment, aircraft, railroad rolling stock, and metalcutting and tooling.

A. WEAR AND PRODUCT DURABILITY

Wear, along with other degradative processes like corrosion, ultraviolet degradation, mildew, rot, etc., is a process that controls the lifetime of products and whose control can increase product durability. As stated in the "Proposal for a Wear Control Handbook" (ref. 1): "With improved use of available control technology, component life could be extended with subsequent reductions in maintenance costs and lost productivity." The summary also states that, for the past 30 years efforts were directed toward innovation in materials and design to reach new technical objectives. Little regard was given to such items as environmental quality and the conservation of materials, energy and human resources. However, there are now increasing pressures to conserve these resources. Conservation can be in part achieved by longer-life equipment which is directly dependent on the wear of components. Longer-life components would conserve strategic materials, conserve the energy to manufacture them, allow them to be effectively reused, and prevent the excess accumulation of scrap due to the wear of a few critical components.

Not only is wear important in determining product durability, but also its action is costly and has other undesirable consequences. For example, the National Commission on Materials Policy (ref. 2) estimated that wear cost the Nation 15 billion dollars per year in materials cost alone. Further information comes from a working group responding to the United Kingdom's Department of Education and Science (ref. 3) which found that with (1) increasing mechanization and automation, (2) greater use of capital-intensive equipment and (3) higher production rates, breakdowns and mechanical failures were becoming increasingly costly. The principal reasons included corrosion and wear with the latter being the predominant factor. Also, the report of the third Henniker Conference of National Materials Policy (ref. 4) discusses Federal encouragement or support of greater utilization of technological and manufacturing innovations and processes which have materials savings capabilities. Wear is listed as one of the three major technical areas affecting utilization of materials and reduced costs. Section I of the National Academy of Sciences Report, "Mineral Resources and the Environment" (ref. 5) cites increased durability and maintainability of products as important tactics for implementing a conservation ethic.

These reports all support the view that control of wear processes can extend the durability of products and that wear is a process that is of considerable cost to the economy. Its control can conserve materials and reduce costs.

B. WEAR CONTROL

Wear is important in many applications of metals, and its control has developed into a sophisticated technology. This technology can be divided into two broad categories:

- Technology concerned with design and materials selection, and
- Technology concerned with prevention and maintenance.

Both categories are considered in managing wear control, and various alternative approaches present themselves for dealing with these. In fact, the methods for choosing among the various approaches have themselves become a well formulated discipline. Typically one must decide whether an inexpensive but short-lived product or a more

expensive long-lived product should be used. This and similar questions can be answered definitely only when the technical options and the costs associated with them are well-defined. Frequently, the answers are based on modern accounting techniques, with taxation policies being important in determining the outcome. The accounting is different for industrial capital equipment on the one hand and consumer items on the other. Rarely do the "externalities" enter into the decision.

However, even with these approaches available, optimum wear-control measures are not always followed. Examples of unscheduled equipment failure due to wear are all too numerous, and many of these could have been foreseen and corrected either in the design stage or with improved procedures for maintenance or prevention. Such equipment failures cost the economy money in lost production time, often have serious public safety consequences, and serve to increase materials consumption, i.e., they are one aspect of what has been called "material wastage". It is this latter point dealing with the conservation of material resources, which has been the impetus for establishing the present workshop on "wear".

The Workshop was designed to explore specifically the material/economic costs of wear to the economy, some aspects of the state of application of wear technology, and the possibilities of increasing product durability by the control of wear; but most of all, its purpose is to ascertain the impacts of increasing durability in order to improve material conservation.

C. WORKSHOP DESCRIPTION

The intent of the workshop was to obtain information on the state of technology in wear and corrosion control and to determine the availability of data. In addition, the workshop attempted to collect data and information on the costs of wear and corrosion in various industries for various products. Such data will be important in assessing the full economic costs of corrosion and wear processes.

1. Scope

Because the full range of products in U.S. industry could not be covered, the Wear Workshop was limited to the following selected products:

- a. Automobiles and Automobile spare parts,
- b. Naval Aircraft Structures/Materials/Components,
- c. Aircraft/Aircraft Propulsion Systems and Components,
- d. Metal-Cutting Machinery and Tools,
- e. Railroad Rolling Stock, and
- f. Construction Equipment
 - Rubber-tired earth-moving equipment
 - Trace-laying tractors

These products were selected on the basis of: (1) their importance in their given sector, (2) their importance in the consumption of materials, (3) their exemplification of different design philosophies, (4) the potential for improvement in, and (5) the variety of causes leading to replacement.

2. Structure

The Workshop included three sections. Section I covered a series of lectures on the key issues followed by several short presentations describing industry commercial policies for wear control and product durability. Section 2 encompassed a number of seminars on consumer products and capital equipment. Representatives of manufacturing and user groups were included in each seminar. It was intended that each seminar address a specific product area. The chairman of each seminar prepared a summary report of the findings/recommendations. The reports were presented during Section 3 to all participants of the Workshop for comment, review, and critiques. The various sections in detail are as follows:

- a. The Expository Session. Lectures were presented on the following topics:
 - 1. The Cost of Wear and Its Control,
 - 2. Methods of Technological Life-Cycle Cost Accounting,
 - 3. The Economics of Durability,

4. The UK Experience in Tribology, and
5. Specific Wear Control Practices and Policies in Various Industries and in Various Sectors of the Economy.

b. The Seminars. Each seminar covered one of the product areas listed above. Each consisted of 10-20 participants with a chairman. The chairman prepared a report based on the discussions in the seminars that attempted to answer the following questions:

- (1) What are the material and economic costs of wear in your industry or for the product under discussion? Cost should be considered to be the following:
 - Replacement costs when replacement is required because of wear;
 - Scheduled maintenance costs; and
 - Unscheduled maintenance or repair costs. These costs should include lost materials and production time because of unscheduled failures. It was recognized that for a given state of technology certain irreducible costs will be incurred in controlling wear. The intent of this discussion was to determine what these irreducible costs are and how well they are approached for the products under study. It was also recognized that a workshop such as this can only give semi-quantitative estimates of costs but an attempt should be made to be as quantitative as possible.
- (2) Are optimum wear-control procedures followed in your industry? Under this the participants considered design practices and maintenance practices.
- (3) If optimum procedures are not followed, why not? Participants specifically considered the following possibilities for lack of optimum wear control:
 - Lack of knowledge and technology transfer;
 - Lack of adequate maintenance and repair practices, or their availability; and
 - Any taxation or accounting practices that might inhibit optimum wear control and hence product durability.
- (4) Could products be made to last longer with improved application of technology? How much longer? Would there be a net increase or a decrease in costs? Could this be brought about by new design practices or new maintenance and repair practices? What would the material savings be?
- (5) Is any form of life-cycle costing used with regard to the product under consideration? What specific methodology do you use? Specify other methodologies for economic appraisal known to you.

- (6) Does your industry have an established wear control/reduction and costs program ?
- (7) How is existing wear control technology implemented ?
- c. Review and Critique Session. Seminar chairmen reported on the results of their seminar for review and critique by all other workshop members.

D. REFERENCES

1. "Proposal for a Wear Control Handbook" American Society of Mechanical Engineers 345 E 47th Street, New York, New York 10017.
2. National Commission Materials Policy, Materials Needs and the Environment, Today and Tomorrow: Final Report, Washington, D.C., U.S. Government Printing Office, 1973.
3. Lubrication (Tribology) A Report on the Present Position & Industry Needs. Her Majesty's Stationary Office, 1966.
4. Henniker III, Requirements for Fulfilling a National Materials Policy, Washington, D.C., Office of Technology Assessment, 1974.
5. Committee on Mineral Resources and the Environment (COMRATE). Mineral Resources and the Environment, Washington, D.C., National Academy of Sciences, 1975. 348 p. (With four separately bound appendices)

CHAPTER II

CHAIRMEN'S REPORTS*

This chapter presents the Chairmen's Reports for the six seminars held at the Workshop on Wear, February 23-25, 1976. As stated in Chapter I, each seminar covered one particular product area: (1) Automobiles and Automobile spare parts, (2) Naval Aircraft Structures/Materials/Components, (3) Aircraft/Aircraft Propulsion Systems and Components, (4) Metal-Cutting Machinery and Tools, (5) Railroad Rolling Stock, and (6) Construction Equipment.

The Chairman for each seminar prepared a report. These reports contain a review and critique of those subjects discussed in each seminar. Any conclusions or recommendations that are stated in the Chairmen's Reports are those of the respective Chairman and should not be attributed to the Office of Technology Assessment or to the Congress.

A. CHAIRMAN'S REPORT FOR SEMINAR #1 -- AUTOMOBILE/SPARE PARTS

1. Highlights of Seminar #1

Automobiles remain in service for many years. During that time, the general conditions under which they operate may change. For example, the general state of street maintenance varies as a consequence of available funds, speed limits change and usage of thawing salts has increased. There are changes in available fuels and lubricants. Some of these changes may not be foreseen at the time the vehicle is developed and introduced into the market. The vehicles are used in a broad spectrum of climate, topography, maintenance, driver characteristics and other factors that affect durability. As a result, they are consumed at different rates due to circumstances that are not controllable by the manufacturer. The importance of wear as a

*A more detailed account of the seminar discussions together with a list of participants are presented in Chapters VII-XII.

factor contributing to retirement of vehicles from service is unknown. It is judged to be less important than obsolescence, sheet metal corrosion and cumulative collision damage. It is theorized that more passenger vehicles are scrapped because the cost of cosmetic repairs or new tires exceeds their current market value, rather than out of consideration for the state of wear or repairability of the power train and running gear. There is not agreement on this point and it merits further examination.

There has been a growing trend toward reduced auto maintenance and repair service at the large self-service or minimum service gasoline stations. This trend, however, has been offset by increased service being made available through the introduction and expansion of auto service centers in major retail outlets, e.g., Sears, Montgomery Ward, K-Mart, J.C. Penney, etc., and by increased service capacity in existing automobile dealers. Vehicle owner education regarding maintenance and minor repairs is one important area in which the ultimate costs of maintenance and repairs may be reduced. To this end the owner's manuals have been improved to make them more understandable. If it becomes evident that consumers want more technical information, the auto manufacturers can readily provide additional information. It is also possible that adult education courses could be instituted to educate people on proper automobile operation and how to perform minor maintenance.

The automobile industry is continually improving diagnostic equipment and techniques as an offset to the increasing complexity of the modern car and to provide a significant improvement of the repair and maintenance function. This equipment, however, is only as good as the auto mechanics that operate it. There is some indication that the life of replacement parts in some cases may be a function of the quality of the repair work rather than the quality of the part. This would place further emphasis on the improved training of auto mechanics. Greater participation by auto mechanics in such programs as the National Institute for Auto Service Excellence Certification (NIASE) is desirable. Another example of the means of upgrading service personnel is the method employed by some auto manufacturers of sending them dealer service-personnel service bulletins and training publications which reflect the latest techniques in identifying and servicing automobile problems.

There are indications that some mandatory inspection systems have resulted in extended car life. This conclusion has been drawn from comparisons of the automobile in Pennsylvania and Illinois, and Virginia and Maryland. Pennsylvania and Virginia, which have had periodic inspection programs for many years, were compared, respectively, with Illinois and Maryland, which do not have such programs. By comparing Pennsylvania with Illinois and Maryland with Virginia, car longevity was evaluated in pairs of states whose size, climate, income distribution and degree of industrialization are comparable. It was found that median car life in the states with inspection programs, Pennsylvania and Virginia, was 7 months and 20 months longer than in the respective noninspection comparison states of Illinois and Maryland. This information was described by D.J. Barrett in his paper entitled, "Automobile Durability" presented on February 23, 1976, at the OTA Workshop on Wear Reduction. There are statistics to show that fleet owners in states requiring inspections do purchase more replacement parts for the brakes, front end suspensions, and exhaust systems than those owners of comparable car fleets in states with no inspection. The potential for material conservation through periodic motor vehicle inspection programs warrants further study.

Advancements in vehicle durability in recent years have been accompanied by significant reductions in the need for scheduled maintenance. Part of this reduction can also be attributed to the improvement in lubricants and lubrication techniques. Further improvement in scheduled maintenance can be anticipated from further research in lubricants, including the use of synthetics, and improved product and component designs. Moreover, new developments in metallurgy and seal technology also should lead to further increases in the intervals between scheduled maintenance.

Unscheduled maintenance and repairs are expected to benefit from the same factors that have improved the scheduled maintenance situation. There are some data which indicate that unscheduled maintenance and repairs account for two to three times the cost of scheduled maintenance.

Data from one fleet operator show only about one unscheduled major repair per car in a 300-unit fleet in the first 35,000 miles per car. (This data is shown in

Table II-1.) This represents the experience with one or two types of vehicles in a particular fleet. Wear experience is known to be different from fleet to fleet and between vehicle types. Vehicles produced for lease and rental fleets now constitute about 20% of total vehicle production. Much more fleet and nonfleet vehicle data is available and should be assembled to arrive at an even better understanding of the importance of automobile wear with respect to material wastage. The Department of Transportation publishes a report periodically entitled Cost of Operating An Automobile and it is an excellent source of maintenance cost data experienced by individual car owners.

2. Answers to Specific Questions Addressed in Seminar #1

The participants of seminar #1 answered those questions stated in Chapter I, Section 2(b) in regard to automobiles and automobile spare parts. The answers to the questions follow.

Question I --

What are the material and economic costs of wear in the automobile spare parts industry? Replacement cost. When replacement is required because of wear, it is not known at the time. However, the cost of material (in its original state) is low in relation to the complete cost including labor. Recovery of metals from retired vehicles and worn parts is estimated to be more than 95%¹. Zinc, aluminum and copper are separated during recovery; whereas, generally chromium and nickel are embodied in the recycled steel. There are, however, some more sophisticated auto shredders which do separate out the chromium and nickel. No doubt this practice will be more widespread in the future. Eighty-two percent of the automobiles retired were recycled during 1965-73. During 1973-74, more vehicles were recycled than were retired from service^{2,3}. This resulted in a reduction in the national inventory of junk vehicles.

¹"The Automobile as a Renewable Resource," L. R. Mahoney and J. J. Harwood Resource Policy, 253-265 (1975).

²"Analysis of Materials in Automobiles," R. L. Polk, U.S. Department of Transportation, Transportation System Center, Report No. PM-T-46 (1975).

³1975 Almanac Issue, Automotive News, April 23, 1975, p. 71.

TABLE II-1. THIS SURVEY* CALCULATED ON 300 UNITS
TRAVELING 10,000,000 MILES

28% Had Transmission Failures
60% of 28% Failures Before 50,000 Miles
1% of 60% in Warranty

6% Had Radiator Failures
74% of 6% Failures Before 50,000 Miles
13% of 74% in Warranty

14% Had Water Pump Failures
75% of 14% Failures Before 50,000 Miles
6% of 75% in Warranty

5% Had Fuel Pump Failures
75% of 5% Failures Before 50,000 Miles
16% of 75% in Warranty

4% Had Valve Jobs Failure
40% of 4% Failures Before 50,000 Miles
20% of 40% in Warranty

14% Had Starters Failures
80% of 14% Failures Before 50,000 Miles
8% of 80% in Warranty

8% Had Differential Failures
64% of 8% Failures Before 50,000 Miles
8% of 64% in Warranty

11% Had Master Cylinder Failures
85% of 11% Failures Before 50,000 Miles
6% of 85% in Warranty

16% Had Power Steering Failures
66% of 16% Failures Before 50,000 Miles
3% of 66% in Warranty

***Provided by the Superintendent of Transportation**
Baltimore County, Maryland -
concerning a fleet made up cars of two manufacturers.

- Scheduled maintenance cost is estimated at 1¢/mile; this is based on fleet operation.
- Unscheduled maintenance or repair cost is estimated in the order of 3¢/mile, depending on size, the cost per mile ranges from 2.5 to 3.4 cents, see Figure II-1. Based on 100 million cars on the road, scheduled and unscheduled maintenance and repair costs amount to about 40 billion dollars per year.

Question 2 --

Are optimum wear-control procedures followed in the automobile/spare parts industry? In terms of design and maintenance specification, sound engineering practice is used. In addition, the major manufacturers have substantial in-house research programs in the areas of design and wear control. Knowledge gained is communicated to the rest of the industry and other industries through the appropriate technical societies. In terms of actual maintenance and operation by owners, practices are variable.

Question 3 --

If optimum procedures are not followed, why not?

- Decrease in repairs. Manufacturers are continuing to strive for a decrease in repairs. There are definite improvements in the life of components such as alternators, batteries, tires, radios, which have been in production for long periods. The owner's adherence to recommended maintenance and repair practices are variable.
- Taxation. It is not obvious that any taxation practice would be helpful at this time.

Question 4 --

Could products be made to last longer with improved application of technology? Significant improvements have been incorporated in vehicles during the past 20 years which have increased the potential life of components and the total vehicle. However, actual life of vehicles has remained relatively stable. During the period 1955-1965, based on R. L. Polk's data, 95% of the automobiles are still registered after 10 years. It appears that this 10-year trend will continue. The potential life of automobiles can be improved with applications of technology and efforts continue to be made.

B. CHAIRMAN'S REPORT FOR SEMINAR #2 -- NAVAL AIRCRAFT STRUCTURES/MATERIALS/COMPONENTS

1. Highlights of Seminar #2

Product durability represents a major goal of two programs being sponsored by the Naval Air Systems Command viz.

SUBURBAN BASED OPERATION

CENTS PER MILE

	ORIGINAL VEHICLE COST DEPRECIATED	MAINTENANCE, ACCESSORIES, PARTS & TIRES	GAS & OIL (EXCLUDING TAXES)	GARAGE, PARKING, & TOLLS	INSURANCE	STATE & FEDERAL TAXES	TOTAL COST
STANDARD SIZE	4.2¢	3.4¢	3.2¢	2.0¢	1.8¢	1.5¢	15.9¢
COMPACT SIZE	2.9¢	2.7¢	2.8¢	2.0¢	1.5¢	1.2¢	12.9¢
SUBCOMPACT SIZE	2.3¢	2.5¢	2.0¢	2.0¢	1.5¢	.9¢	11.2¢

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration
Office of Highway Planning
Highway Statistics Division
April 1974

Figure II-1. Cost of Operating an Automobile

- Analytical Rework Program
- Service Life Program - NavAir Program directed by Captain G. Klett for Service Life Extension was also described in depth.

Wear control represents one of several thrusts to achieve improved product durability and includes (a) new technology for wear reduction; (b) improved wear-prevention materials and implementation of procedures for reducing wear (technology transfer).

The cost of wear has also been the subject of recent studies and examples of such costs are as follows for one aircraft through one service period:

Intermediate/Organizational Level

Component Maintenance (Unscheduled)	\$140/flight hour
Component Maintenance (Scheduled)	\$ 67/flight hour
Depot Rework:	
Component Rework (Concurrent)	\$ 20/flight hour
Discrepancies	1.70/flight hour
Tech Directives	12.87/flight hour
Materials	3.30/flight hour
<u>Total Cost for Wear</u>	\$245/flight hour
<u>Total Cost for Fuel</u>	\$376/flight hour

Examples of the total yearly cost of wear on other components:

(1) Attack Aircraft (T/M/S) Autopilot Servovalves	\$ 100,000
(2) Fighter Aircraft (T/M/S) Brake Wear	2,031,000
(3) Attack Aircraft (T/M/S) Brake Wear	789,000
(4) Attack Aircraft (T/M/S) Speed Brake Actuator	91,760

This data represents the direct cost of wear and does not include such information as overhead costs, down time, support and supply system costs and spare parts. However, a logistic support analysis technique is available which can take such factors into account. Using this technique, any given proposed life improvement of a component can be quantified as to the total cost benefits to the Navy system. Thus,

it is concluded that the economic benefits of increased durability can be determined using present methods for much Navy equipment and by inference for other military equipment as well.

It is concluded that military wastage as scrap is small. Almost all materials except titanium are recycled. In addition, manufacturers have active programs to optimize the use of material, for example by using damaged materials in less critical applications and optimum metal cutting procedures. The only recognizable wastage is that due to an excess of spare parts required for logistic support. Improvements in wear and durability can have a direct impact on the number of spares required. Less spares represent not only reduced materials but also considerable savings in logistics support costs. Therefore, a significant impact can be achieved in materials conservation including precise estimates of the materials saved.

Life-cycle costing represents the most realistic approach to economic estimates concerning acquisition and ownership. This subject was reviewed in depth during a recent 3-day meeting sponsored by OSD and the proceedings can be made available for review/implementation. In terms of reducing life cycle costs, wear reduction procedures for minimizing maintenance requirements can produce a major benefit. An example of this is life cycle costing of Navy aircraft tires. An example of costs involved for a main gear tire:

Planned Failure Rate -- 26 Landings/Tire

Basic Tire Cost	- \$70.40	Yearly usage	- \$ 20,500
Labor Cost	- \$20.00	Cost/landing	- \$ 3.48
Total Cost/Tire	- \$90.40	Total Yearly Cost	- \$1,853,200

Worn Navy aircraft tires are not discarded. Because of the wide interest in conserving materials and dollars, the Navy requires that all new aircraft tire carcasses be designed for multiple rebuilding. The rebuilt tire, when returned to service, provides additional landings equal to those of the original new tire at approximately one-fourth the new tire cost. Numerous tire-carass rebuilding ensures maximum utilization of the original tire carcass at minimal cost.

The life-cycle cost concept for Navy tire procurement has motivated industry to provide tires which have progressively improved tire performance and reduced maintenance man-hours. It has also resulted in greater safety, as well as improved conservation of imported materials resources. Life-cycle costing for aircraft tires has significantly increased tire reliability while effectively reducing operating cost.

2. Answers to Specific Questions Addressed in Seminar #2

The participants in seminar #2 answered those questions stated in Chapter I, Section 2(b) in regard to naval aircraft structures/materials/components. The answers to the questions follow:

Question 2 --

Are optimum wear control procedures followed in the naval aircraft structures/materials components/industry? In evaluating the question of the application of optimum procedures for wear control, the following constraints require recognition:

- Lack of accepted wear control design procedures,
- Lack of an effective feedback mechanism to implement improvements from maintenance actions to new production or manufacturing,
- Timeliness of specifications/handbooks.

In further pursuit of the question, the Navy Program employs a continuous liaison effort involving experts from industry, universities, research institutes and government in wear-related maintenance problems. Such effort represents one method in attempting to employ the most effective (optimum) wear procedures. Some recognized limitations of optimum wear control methods include: (1) methodology of technology transfer, (2) availability of processing equipment, and (3) training.

Results achieved under the Navy Program have adequately demonstrated that equipment and components can be made to last longer with the application of available technology, e.g.

<u>Part Designation</u>	<u>Results</u>
Cutting tools	400% Life Increase
Control cable	100% Life Increase
Electrical connectors	400+% Life Increase

An estimate of the cost avoidance for the electrical-connector example is 16,000 maintenance man-hours for a period of one year.

Materials-savings data, although not immediately available, can be quantified.

In completing this preliminary assignment in preparation of the OTA assessment, a list of materials encompassing aluminum, steel, copper, and several different alloys as well as non metallics was compiled by the Naval Air Systems Command.

An estimate of material savings accumulated can be calculated from service life improvements/extensions of aircraft as well as aircraft components.

C. CHAIRMAN'S REPORT FOR SEMINAR #3 -- AIRCRAFT/AIRCRAFT PROPULSION SYSTEMS AND COMPONENTS

1. Highlights of Seminar #3

This report is a summary of nine hours of seminar deliberations held on the subject of wear control in aircraft propulsion systems. The 16 participants included representatives from aircraft engine and helicopter transmission manufacturers, bearing and petroleum industries, commercial airline and military users, U.K. and other U.S. Government organizations, and university and research institutes.

The report is divided into three sections. First, the relevance of wear control to aircraft propulsion technology will be evaluated in general terms. Second, six questions addressed by the seminar participants are examined. And third, certain critical areas where current knowledge is inadequate, and where properly directed research and development will, in the participant's collective judgment, substantially enhance reliability and safety, reduce maintenance and operating costs, and conserve critical material is enumerated.

2. Importance of Wear Control

In order to provide a proper perspective to the seminar's discussions, the participants felt that it was necessary to answer first a basic question, namely, how important is wear control in aircraft propulsion systems to the total economic and materials conservation outlooks of the nation? The participants recognize that, by its very nature,

aircraft propulsion is a highly developed technology, but not a large consumer of materials. However, it is an important consumer of materials in critical supply, which include not only metals but also fuel.

In aircraft operation, safety must certainly be the overriding consideration. In average commercial airline service, safety is achieved by employing a high degree of redundancy in terms of engines and certain critical components. Within this context, the reliability or life of system components becomes basically a hidden economic issue; and the potential benefits of wear control cannot be readily assessed on the basis of the current state of airline economics. However, with single-engine aircraft and helicopters, reliability and safety are synonymous; thus the importance of wear control relative to reliability and safety as well as cost is clear.

Taken as a whole, it is the participants' consensus that the benefits to be derived from effective wear control are alike regardless of the nature of aircraft service. These benefits are as follows:

- a. Reduced maintenance and replacement costs.
- b. Improved propulsion system performance and fuel cost.
- c. Conservation of critical materials.
- d. Technology spin-off, which benefits other industries.

It is estimated that aircraft propulsion (engines and transmissions) is currently a \$4-billion dollar industry. A recent study conducted by the Navy on the operating costs of one aircraft* shows that the total cost of wear is \$245/flight hour as compared to the total cost of fuel of \$376/flight hour. Of course, the propulsion system is not the sole contributor to the total cost of wear on an aircraft. So far as the propulsion system alone is concerned, it is our opinion that with adequate development and Governmental encouragement, savings of 50% in materials, 10% in fuel consumption, and at least 50% in maintenance and replacement costs, can be realized within one decade.

*"Proceedings, Wear Control for Naval Aircraft," Naval Aircraft Materials/Processes Meeting, 4th Annual Meeting, Aeronautical Analytical Rework Program, 2-4 Dec. 1975, Naval Air Development Center, Warminster, Pa.

3. Answers to Specific Questions Addressed in Seminar #3

The participants in seminar #3 answered those questions stated in Chapter I, Section 2(b) in regard to aircraft/aircraft propulsion systems and components. The answers to the questions follow:

Question 2 --

Are optimum wear -- control procedures followed in the aircraft industry?
The answer from the commercial airline sector is a qualified "yes," with on-condition maintenance. However, it is pointed out that the procedure can be improved if reliable condition monitoring instrumentation is available. The process can also be made more efficient with improved labor skills and motivation.

The answer from the military sector is also a qualified "yes," with the military generally changing over from scheduled maintenance to on-condition maintenance. In addition to the problems faced by the airlines, the storage and handling of replacement parts in the military supply system have been difficult. Moreover, where scheduled maintenance is practiced, reliable determination of the usability of the removed parts also presents a problem.

Question 3 --

If optimum procedures are not followed, why not? Seminar #3 answers are as follows:

- a. Generally speaking, the problem has not been the lack of basic available knowledge, but a lack of timely technology transfer in usable form. On the design side, due to a lack of adequate financial support for intermediate development, the design has tended toward conservatism. On the maintenance side, current knowledge needs to be put into practice and improved technology (such as in-flight condition monitoring) can provide further advances. Governmental support in both areas is considered crucial.
- b. It is believed that Governmental support may possibly be directed along the following lines:
 - Taxation and accounting policies designed to encourage savings in maintenance cost and materials conservation
 - Better balance and simplification of regulatory procedures,
 - Direct financial support to accelerate the tempo of improvements, particularly in the area of intermediate development mentioned above, and
 - Direct financial support in research in certain critical areas (See later discussion of critical areas).

Question 4 --

Could products be made to last longer with improved application of technology? Seminar #4's answer to this question is a resounding "yes."

It is necessary to identify the various failure processes and have a better understanding of their impact, which will help in the long run. However, even on the short range, the research laboratories have shown that new materials and lubricants with substantially better wear and other attributes are now available, and these are not necessarily the ultimate obtainable. By merely taking advantage of these available new materials and lubricants, and with improved designs, the engine and helicopter manufacturers have proposed designs which, given timely and adequate financial support, can, within one decade, yield estimated savings of 50% in materials, 10% in fuel consumption, and at least 50% in maintenance and replacement costs.

Question 5 --

Is any form of life-cycle costing used with regard to the aircraft industry?

In the matter of life-cycle cost, there is at present no wide-based quantitative knowledge to guide its application. However, it is believed that such information is currently available at the commercial airlines and will in time also be available from the military. Government-sponsored surveys and analyses of such information should go a long way toward establishing the needed data base.

Regarding the long-term application of life-cycle costing, the participants of seminar #3 believe that the following factors should be taken into consideration:

- a. The inflation of dollar value.
- b. The capricious nature of fuel cost.
- c. The impact of mission profile, i. e., short missions vs. long missions. The problem here is akin to the stop-and-go automobile operation vs. sustained highway driving.
- d. The impact of propulsion system performance and performance degradation in service. In this respect, the relative weight to be assigned to cost and performance is expected to be different for commercial and military operations.
- e. Initial equipment cost vs. spare parts cost. How can a realistic balance be made?
- f. The question of warranty. The current commercial procurement practice is for the propulsion system manufacturer to assume the warranty responsibility, while in Government procurements the responsibility rests, except for some isolated instances, with the Government. How these different procurement practices affect the life-cycle cost appears to merit study.

In this connection, a NASA report* is of interest. Among the conclusions reached in this study were: (a) During the initial 5-year period after a new design has been put into service, the maintenance cost was high. However, during the "mature period" after the initial problems had been solved, the maintenance cost reduced to about one-half to one-third of the initial. (b) There was no significant difference between military-derived vs. commercially-derived propulsion systems in life-cycle costs.

Seminar #3 participants believe that the high initial maintenance cost cited above is due to the lack of intermediate development previously mentioned. In the instance of commercial airlines, this means in effect that the airlines are paying the lion's share of the intermediate development cost, which cost must in turn be passed on to the customers. In the case of military service, the cost of intermediate development is in effect borne by the Government, or the general public. Perhaps direct Government support of intermediate development would be more effective and more economical in the long-run.

Question 6 --

Does your industry have an established wear-control/reduction and costs program? The answer from the commercial airlines is a qualified "yes," with on-condition maintenance. The answer from the military is also a qualified "yes," with the Navy having already implemented on-condition maintenance, but as yet not enough experience to provide details. The Air Force and the Army are tending toward this direction, with on-going programs on reliability and maintainability studies.

Question 7 --

Is existing wear-control technology implemented? The answer is generally "yes," but not separately identified in the organizational structure.

4. Critical Problem Areas

It is the judgment of the seminar #3 participants that research and development in the following areas are warranted:

- a. Engine gas path sealing - This problem is important because it directly affects fuel economy, compressor stall margin, and reliability and maintenance cost.

*Sallee, G. P., "Economic Effects of Propulsion System Technology on Existing and Future Aircraft," NASA CR-134645.

Currently, the use of abradable material provides a solution, but optimum material selection requires research and development. For future engines, research directed toward the development of a better sealing technology is deemed necessary.

- b. Blade erosion - Research on the development of optimum abrasion-resistant material is required.
- c. Liquid sealing - The present technology for liquid sealing in engines and transmissions is deemed inadequate. There is a need for basic and applied research.
- d. Fretting - Research to enhance our understanding and practical control of fretting is needed.
- e. Bearings, gears, lubricants - As mentioned earlier, the feasibility of a very substantial savings in critical materials and life-cycle cost, not to mention improved reliability and safety, has already been demonstrated in the research laboratories. Engineering development to realize these gains in practice is urgently required.
- f. Contamination control - The importance of contamination control has been emphasized, for example, by the Navy study previously mentioned. Techniques of contamination monitoring and control require development.
- g. Predictive techniques - Better techniques for predicting system reliability, performance, and initial and maintenance costs in the design stage are urgently needed. This implies a need for research to achieve a better understanding of the failure mechanisms.
- h. The technology for high-speed rotating components requires development.
- i. A better understanding of thermal control and cooling, both basic and applied, is urgently required.
- j. A wide-based and in-depth survey and analysis of costs and cost distribution in current practice is required to provide the baseline data needed, not only on its own merit, but also for extrapolation to future applications.

5. Conclusion

The participants appreciate the efforts of the Office of Technology Assessment in organizing this Workshop and the Seminar on Aircraft Propulsion Systems. The participants came from dissimilar professional backgrounds and vantage points, but leave with the same convictions that effective wear control benefits all segments of our industry and that much can indeed be done to reduce wear, improve reliability and safety, conserve critical materials, and reduce life-cycle cost. The participants submit once again that

aircraft propulsion is a technology leader. Any investment in bringing about effective wear control technology in this area will benefit many other industries; and the total benefit cannot be measured by dollars.

D. CHAIRMAN'S REPORT FOR SEMINAR #4 -- METAL-CUTTING MACHINERY AND TOOLS

The following general conclusions and recommendations have been prepared on the basis of comments, revisions, and additional supporting data supplied by the participants of seminar #4.

1. State-of-Technology

- a. Control of wear in metalcutting machinery and cutting tools must be considered through its impact on the total manufacturing system in which metalcutting is performed using metalcutting machine tools and cutting tools. The "Productivity" and "Leadership" of the U.S. manufacturing sector, especially in the area of computer aided manufacturing, is in jeopardy due to the lack of Government support.
- b. The cost of machining in the U.S. is estimated to be about \$54 to \$65 billion per year. These costs can be reduced by (1) implementation of proven techniques and (2) development of improved technology.
- c. The material removal operations such as machining and grinding are used to produce surfaces that are involved in sliding and rotating type contacts. The surface integrity imparted by these material removal processes has a profound influence on the product performance and durability.
- d. Cutting tool and grinding wheel wear processes are quite different than those involved in sliding and rotating, such as in bearing surfaces. The prediction and control of cutting tools and grinding wheel wear is a key factor in manufacturing costs and productivity.
- e. The present carbide cutting tool technology is based on tungsten carbide. Tungsten is also an important alloying element in high speed steels used for cutting tools. Presently, roughly 25 to 30 percent of tungsten is imported; however by 1987, over 75 percent of the tungsten will have to be imported, primarily from socialist block countries. *

*"Trends of Usage of Tungsten," National Materials Advisory Board (NAS-NAE), Report PB-223716, July 1973, Distributed by NTIS.

- f. About 7 million pounds of carbide tools and 41 million pounds of HSS tools are annually used in the U.S.A. Only about 0.3% of each carbide tool is worn away, the remaining is recycled to rock bits and tire studs. About 1/3 of each HSS tool is ground off during resharpener. Carbide and HSS cutting tools also fail due to fracture. Annually, estimated \$2-8 billion spent in purchasing, changing and regrinding cutting tools, including labor costs but not including overhead and lost production costs.
- g. Machine tools are not generally replaced because of wear. The replacement is due to loss of operational capability (speed, horsepower, accuracy, and rate of metal removal) or due to new machine tool technology. Scheduled maintenance is generally arranged at nonproductive time. Unscheduled maintenance occurs because of mechanical, electrical or hydraulic system failures. The greatest economic costs of wear in machine tools is in the cost of lost opportunities due to unanticipated down time. To maintain U.S. machine tool industry competitive, economic incentives such as investment credit and factory writeoffs should be considered. American Machinists estimates that yearly, \$1 billion are spent due to the use of out-dated machine tools.
- h. Cutting fluid replacement is needed to maintain proper proportions and concentration. The cost of cutting fluid disposal may range as high as 115% of the cost of cutting fluid. Closed loop cutting fluid systems are being developed to minimize replacement costs.
- i. The loss of work material in the form of chips and scrapped parts in metal-cutting can be substantial. From material conservation point of view, these costs need to be estimated. Significant material cost earnings can be achieved by near-net-shape and net-shape metal working processes such as isothermal forging and hot isostatic powder-metallurgy techniques. However, the effect of these processes and subsequent finish machining operations on product durability needs to be established.

2. Cost Estimates

The workshop developed cost estimates for cutting tools, on the basis of the data provided by Dr. John Mayer, Jr. (See Table II-2). No cost estimates were available for workpiece material conservation, wear cost of machine tools, and the replacement costs of cutting fluids.

3. Recommendations

- a. In view of the state-of-technology items (a), (b), (c) and (d), systematic research, development, and implementation programs are needed in manufacturing technology, especially computer aided manufacturing.

TABLE II-2

Data provided by Dr. John Mayer, Jr. in summary of seminar #4
(Chairman V.A. Tipnis)

Initial Purchase Cost and Material and Tool Wear for Metalcutting Tools:

a) High-Speed-Steel (HSS) Tools:

	PURCHASE COST AND MATERIAL			ENTIRE LIFE TOTAL WEAR QUANTITY		TOTAL GROUND OFF DURING ALL RESHARPENING	
	Million Dollars/ Yr	Million Units/ Yr	Million Lbs/ Yr	1,000 Lbs/ Yr	% of Tool Weight	Million Lbs/ Yr	% of Tool Weight
U.S.	470 ¹	157	40.8	40.8 ²	0.1	13.6 ²	33

¹U.S. Department of Commerce, 1974.

²Lost and not recycled.

b) Carbide Tools:

	PURCHASE COST AND MATERIAL			TOTAL WEAR QUANTITY	
	Million Dollars/ Yr	Million Units/ Yr	Million Lbs/ Yr	1,000 Lbs/ Yr	% of Tool Weight
U.S.	435 ¹	334	6.9 ²	20.7 ³	0.3

¹U.S. Department of Commerce, 1974.

²Recycled but not as carbide cutting tools; used in making studs for tires and rock bits.

³Lost and not recycled.

- b. In view of the state-of-technology items (e), and (f) alternative cutting tool technology should be developed based on indigenously available materials such as titanium carbide and others.
- c. In view of the state-of-technology item (g), economic incentives should be provided to promote the use of more productive machine tools.
- d. In view of the state-of-technology items (h) and (i), the development of manufacturing processes that conserve critical and strategic materials should be promoted.
- e. The workshop participants felt that there should be programs through which a closer cooperation between the academia, research laboratories and manufacturing industries can be established. In Europe and Japan, such a closer cooperation has lead to national projects in computer aided manufacturing.

E. CHAIRMAN'S REPORT FOR SEMINAR #5 -- RAILROAD ROLLING STOCK

1. Highlights of Seminar #5

A full day of discussions were held. Twenty-three persons attended the meetings, all but a very few of them being there the whole time, and sixteen made formal presentations. It was the consensus of those present that a full and frank discussion of the issues involving railroad wear was achieved.

2. Answers to Specific Questions Addressed in Seminar #5

The participants in seminar #5 answered those questions stated in Chapter I, Section 2(b) in regard to railroad rolling stock. The answers to the questions follow.

Question 1 --

What are the costs associated with wear in the railroad industry? Many of the participants provided overall estimates, while many others produced unit costs associated with various individual items or maintenance procedures. To give some examples:

Replacement and remanufacture of roller bearings in freight cars costs \$15 million per year.

750,000 worn freight wheels were replaced last year at a cost of \$140 million.

One million tons of new rail was installed to replace old rail at a cost of \$250 million.

Maintenance and repair costs of locomotives total \$665 million per year (\$.36 per 1000 gross ton mile).

Finally, an all inclusive item, that includes damage from other factors than wear is maintenance of way which totalled over five billion dollars in 1974.

The Chairman's personal interpretation of these data is that the damage caused by wear in the railroad industry totals some 3 billion to 4 billion dollars per year. This is consistent with a feeling the Chairman has had for some time that the total damage in the U.S. done by wear amounts to some 100 billion dollars a year; the two main components being automobiles and clothing.

Question 2 --

Are optimum wear-control procedures followed? The consensus was that in general they were not, and a number of reasons were advanced. One general comment was that there was much ignorance about wear, and hence it was not always possible to institute procedures that would minimize wear. But even when such procedures were available, they were generally not followed for reasons such as the following.

When a supplier offered a new and improved component, with higher wear resistance, but costing 1.5% more, many railroads refused to buy it, because they couldn't afford to pay the extra amount, or were not clear as to the potential benefit.

A new and improved component that might need maintenance work away from its home railroad was considered uneconomical, because it was likely to be removed and replaced by the original component. In fact this was a theme of several comments in several different settings. The fact that cars are often used by other railroads (interchange service), and that many components and repair procedures need industry-wide approval, act as a deterrence to progress in spending more money and installing more wear resistant components on rolling stock. Progress was most likely to be made in unit trains, which always take a scheduled route. Such trains, however, provide a "real service" means to evaluate new technology as it becomes available.

(There was a considerable amount of discussion of the peculiar nature of the industry, with its great interdependence. This has led to many good effects, like the setting of standards and the keeping of good statistics, but it does discourage individual pioneering and initiative).

As to rail, a more bizarre situation emerged. High strength heat treated rail is shown to be more wear resistant by a factor of two or three or more and costs only 40% more. But one railroad has tried unsuccessfully for more than a year to get this material. Facilities for producing it are limited, and little is being done to remedy the situation by increasing output. Presumably the financial returns and the assurance of a long term market are not sufficient for the steel manufacturers. It is also possible that capital investments for meeting pollution control regulations took higher priority for limited funds available and pollution control demand for available capital.

The only possible exception to this picture was provided by an engine builder. In this case there seemed to be a steady improvement both in performance capability and in wear life. I wonder whether the concentrated nature of this industry might make technical innovation more attractive.

Indicently, some component manufacturers are very active in investigating failures and wear out behavior of their components, others are not, but apparently both types remain in business.

Question 4 --

Could products be made to last longer with improved application of technology?
There was a general consensus that in many cases they could, but there were provisos. Some railroads could not, or would not, pay the larger levels of first costs associated with improved wear resistance. In other cases, the improved materials would be harder to incorporate (e.g., by welding). Thus, given a work force of uncertain skill levels, e.g., adequately qualified welders, there might be a trade-off between higher wear life and higher reliability. In fact, there was some feeling that this factor was already operating, leading (in the case of steels to be welded) to the use of less wear resistant steels than were readily available. (The fact that there were many repair shops spread around the industry, with variations in levels of sophistication tended to inhibit the use of steels which were not easy to process.) A remedy might be to use low alloy steels, rather than plain carbon steels since low alloy steels of lower % c are easier to weld than plain carbon steels of the same hardness, but higher % c.

Examples were given where increases in life by factors of three seemed achievable, and all in all it seems that a decrease in wear rates by a factor of two might be a realistic target. More effective use of track lubrication, for example, should be

considered. One problem with the industry is, however, that as soon as the wear life is increased markedly there is a tendency to change the operating conditions (for example by increasing axle loadings) so as to nullify the benefit obtained.

It might be mentioned that examples were introduced of cases in which wear improvements in one component led to deterioration in another component. Thus the use of rolling contact bearings in trucks led to a greater lateral stiffness that reduced damping potentialities, and led to increases of wear in the center bowl-centerplate system. The use of harder rails might, in some circumstances, lead to increased wheel wear. Also in rail wear there was some expression of opinion that a relatively mild wear had desirable consequences, in that it prevented fatigue and surface fatigue failures.

The "materials benefits" of a lower wear rate would be fewer steel particles strewn around the countryside, but this was felt to be less significant than lowering the maintenance and installation costs associated with wear.

Question 6 --

Does industry have established wear reduction programs and how are they implemented? It was generally agreed that industry has done little research work in the area of wear reduction, and that more work is both appropriate, and likely to be highly productive.

In the past, industry has mainly reacted to aggravated problems, like a rash of failures (especially unanticipated failures), rather than to long-term annoyances already budgeted for, like wear. In fact, until there are quantitative models of what wear is reasonable, there are few methods of judging what proportion of the costs associated with wear are preventable.

There is very little university interest in railroad wear research (although we heard reports from two funded projects), and little industrial research in this country (though there are two active research programs in Canada). It is hoped that IFAST (a new full scale testing facility in Pueblo, Colorado) will generate useful wear data. There was some discussion whether government sponsorship of industrial research could be increased and the general feeling was that this might be very cost-effective.

It was explained that the focus of recent government interest has been increased reliability rather than increased wear resistance. Thus, the sponsorship of programs to reduce wear would represent a shift in priorities.

Question 7 --

How is existing wear-control technology implemented? Long-range aspects -- Looking into the distant future, it was felt that in an era in which fossil fuels were less readily available but electricity produced by fission or fusion processes were the main source of energy, it was important to have available a healthy transportation system which can operate on electricity, and is highly energy-efficient as well. The railroad industry clearly fits this description.

In fact, past procedures have favored other modes of transportation. For example, the military has largely paid for development costs for the aircraft industry. Interstate highways and related use costs have favored truck transportation. These policies have adversely affected the health of the railroad industry. Accordingly, remedial steps were felt to be worthy of consideration.

F. CHAIRMAN'S REPORT FOR SEMINAR #6 -- CONSTRUCTION EQUIPMENT

1. Highlights of Seminar #6

The segment of the Heavy Construction Equipment Industry that was represented by persons attending the workshop was that large portion that builds earthmoving machines. This, therefore, excluded such machines as tower cranes, asphalt mix plants and paving machines from the discussions.

There were representatives of four manufacturers, two dealers and two contractors.

a. Characteristics of the Earthmoving Machinery Industry

The following are some of the more important characteristics of this industry:

1. Large volume of business -- many billions annually in the sale of new machines, new parts, dealer services, and sale of remanufactured and rebuilt parts.
2. Detailed product knowledge transmitted back and forth among manufacturer, dealer, and customer.
3. Large initial investment per machine -- typically \$25,000 to \$250,000 each.
4. Often get moved from job to job and state to state.
5. Designed to work in an extreme variety of soils and other job conditions.

6. Contain an especially high portion of castings, forgings and heavy welded structures -- all of these requiring a high tooling investment by the manufacturer.
7. Selling and servicing mostly done by franchised dealers who are independently owned.
 - These dealers typically have a long term of experience -- 20, 30, 40 years is very common. This allows building up good managerial experience and skilled worker experience with this class of machines.
8. Users range from very small operations -- with only one or two machines -- to very large contractors owning hundreds of machines.
 - Users include municipalities who use the machines for maintenance of streets and for landfill methods of waste disposal. Townships and counties own machines for rural road maintenance. Several segments of the federal government own machines -- examples are the army engineers and the forest service.

b. Manufacturers' Progress in Extending Wear Life

The normal competitive forces and the manufacturer-dealer-customer close relationships have worked to progressively result in significant improvements in wear life to occur throughout the past. One of these forces is the users' dissatisfaction with the unsatisfactory life of a particular part of the machine which has become out of balance with the endurance life of the surrounding parts.

Another strong motivating factor is the competition the original machine manufacturer faces from independent manufacturers who specialize in making and selling high volume wear items in competition for after market parts sales.

Competition for business results in measures to increase the salability of existing machines through performance increases.

Performance increases frequently involve an increase in engine power in order to attain faster machine functions under load. Each increase in performance is likely to have the effect of increasing the operating stresses on some portions of the machine. The parts that are likely to be affected are evaluated on the drawing board, in the laboratory, and through proof testing on the machine before release for production. The evaluation often results in refinements in shape, in material selection or in heat

treatment to allow the part to operate at a higher stress level and, therefore, perform more work for a given weight of material. The result of this application of technology is to conserve the use of materials by refinements of the design to bring the machine components into better balance with each other through identifying those components which have proved to be the less durable ones in the face of overall machine performance increases.

Another motivating force that causes the manufacturer to improve the durability of components is the user's efforts to extend the machine operation into a more hostile working environment. As machines move toward the rough end of the job severity spectrum and get into larger rock and into more abrasive soils it becomes more economically feasible to add costs to the original machine to cope with these environments. With the increasing application of improved materials and heat treatment the result is to attain more wear life through modern design and manufacturing rather than to merely add on more iron.

The above mentioned points can be illustrated by explaining the function and use of a large tractor-scraper. The function of such a machine is to load material into its bowl and haul and spread it on the fill. The machine works frequently in a cloud of abrasive air. This kind of working environment has required over the years a cooperative development program between the earthmoving machine manufacturer and the suppliers to the industry. Much improved filters were developed to keep the abrasives from entering any part of the powertrain including engine, transmission and gear boxes to the driving wheels. The engine air cleaning system uses precleaners and cellulose fiber air filters which are a very major advance over the former "oil bath" air cleaner that used an oil soaked mat of brass turnings. Similarly, advances have been accomplished through improving the efficiency and capacity of filters for the transmission oil and for the engine fuel oil.

Other areas of advancement include superior materials in lip seals for shafts at the point of entry into oil compartments. Modern synthetic elastomers have been developed to withstand the combined effects of lubricants, heat, and cold starting and still retain the proper balance of flexibility and hardness for wear life.

The advancements also include better breathers and better gasketing materials.

Thus the wear life of internal components has been extended considerably through better seals to keep out the very harmful abrasives found around most earthmoving jobs.

The gooseneck and draft frame assembly is a good example of the kind of large welded structure which must withstand high cyclic loads in field service. In seminar #6's work session, one of the manufacturer's representatives traced the methods his company uses to refine the design so as to develop a structure that is efficient in the utilization of steel and which is designed for an adequate number of hours of service when the machine is subjected to loads at the severe end of the normal job spectrum.

The design aids used include such advanced techniques as finite-element analysis. This calculation method requires the availability of modern computers to run the thousands of calculations.

Other aids used by this manufacturer include the use of stress coat in the laboratory. Available also are portable recording instruments that can be mounted on the machine in the field to make counts of the number of excursions of stress per day into zones which would result in ultimate fatigue damage. Such data is needed for later input for full-scale bed-plate fatigue tests to be run in the laboratory.

Laboratory fatigue tests are also very commonly run on other kinds of components, such as axle shafts, engine, and driveline components.

An examination of a crawler tractor equipped with a bulldozer blade points out areas where heat-treated plate is used to gain the advantage of hardness for improved abrasive wear life, and for better indentation resistance for those parts that are subjected to direct impacts against rocks. The moldboard of this bulldozer uses a welding grade of plate heat treated at the steel mill. Twenty-some years ago this kind of large water-quenched heat-treated plate was not readily available to the industry, but increasing demand caused the steel companies to invest in the heat treat facilities. The plate is now commonly used by the manufacturer in several portions of his machines. Heat treated plate is also purchased by the user for replating worn areas.

A further examination of the undercarriage portion of a crawler tractor shows that such an area can be subjected to high impact and abrasive wear conditions. One of the dealer representatives at seminar #6 stated that the undercarriage represents about one-half of the weight of the machine and almost one-half of the ultimate wear and replacement cost in the life of the machine. The majority of the moving parts is composed of heat treated rolled sections, forgings and other heat treated parts. Twenty years ago, these track rollers were greased at 10 to 50 hour intervals. The seals were faced with leather or cork and had a short life. When the seals failed, the lack of lubrication frequently destroyed the shaft and other internal parts. Now these rollers are lubricated with oil and are sealed with metal-to-metal seals able to retain the oil such that the relubrication intervals are 1000 hours and longer.

A recent and modern advancement is the availability of improved track pin seals so that the pin-to-bushing joint can now be lubricated.

Another fairly recent advancement is in improved engaging couplings such as *steering clutches and steering brakes*. A few years ago, these operated in a dry compartment. The dry friction surfaces generated considerable heat and caused deterioration due to heat. These friction plates were expensive. Also there was frequent downtime for adjustment and replacement.

Now used in many crawler machines are oil-cooled steering clutches and oil-cooled brakes. Oil is pumped to the engaging surfaces and provides both cooling and lubrication for the friction surfaces. Here is a dramatic example of material conservation through reducing loss due to wear. The reduced downtime provides another form of conservation of materials by allowing the machine to work more hours per day.

c. Chipless Methods of Forming Parts

Available to the manufacturer today are techniques that allow the economic manufacture of parts through methods of producing finished dimensions without machining. Following are some examples in current production.

- Track bushings are cold extruded from solid barstock.
- Sintered powder-metal parts, for example a hydraulic tube flange, can be produced to a high strength level without any machining.

- Gears are used in the differential housing of a wheel loader. The teeth are forged to finish profile.
- Steel casting which will be welded to steel parts to make a water-cooled exhaust manifold for a marine engine. Several machine operations were eliminated through the improved tolerance control achieved with the investment mold process.

d. Aids Provided by the Manufacturer to the Dealer and Customer

A form of conservation of materials lies in the proper and economical way which the machine is applied to the job conditions and how the machine is maintained. In the earthmoving equipment industry the manufacturer does a considerable amount of work in these areas and provides training aids and instructions in several forms. Among these are (1) guides for choosing the proper machine for the job condition, (2) how to conduct productivity studies, and (3) how to maintain and service the machines. The aids include conducting training schools. Illustrative of the training aids provided by the manufacturer are:

- A book called Understanding Undercarriage which provides information on the proper application and selection of track shoes, periodic inspection methods for determining rate and type of wear, and instructions for rebuild or replacement.
- A book called Guideline for Reusable Parts which is devoted to transmission clutch plates and disc assemblies. This pamphlet shows examples of scored and overheated material that results in parts that are beyond repair and salvage. The book also shows other photographs of parts that appear to be worn at first glance but may be worn only to 10% of expected wear limit. These illustrations show that the plates can be reinstalled with no reconditioning or very minor reconditioning.

e. Remanufacturing

A recent development is the activity of the manufacturers to provide remanufacturing plants. One of seminar #6 manufacturer's representatives described such a new structure. It is an 80,000 square foot facility. The investment cost was \$10 million. The facility is designed to receive worn parts from the dealer organization and rebuild these back to the original equipment standards. Slide photographs were used to illustrate steam cleaning equipment for the engine prior to disassembly. A photograph was shown of a cylinder block after the paint was completely stripped in order to allow for minute

inspection. A boring machine is capable of reconditioning the block bores for the wet cylinder liners. Photographs were shown of magnetic flux equipment for inspecting crankshafts prior to reconditioning. A grinding machine is used for regrinding the cam profile of camshafts. Large size high pressure hydraulic valves are reconditioned by cleaning, rehonoring and refitting. Equipment is available for rehonoring very large size hydraulic cylinders.

f. The Dealer

The equipment dealer contributes toward the conservation of materials in a number of ways. One of these is to install a facility to rebuild undercarriage parts. One of the dealer's representatives at seminar #6 described a typical dealer rebuild shop. Such rebuild facilities have been in common use since World War II when the shortage of undercarriage parts accelerated such a movement.

A point that was emphasized in the workshop was that when parts must be finally discarded, either because they do not lend themselves to economical rebuild or because they have reached the maximum practical number of rebuilds, the scrapped part is still maintained in the materials cycle. Earthmoving equipment parts provide a grade of scrap that commands a 25% premium on the scrap market.

g. Dealer Exchange Programs

Many earthmoving equipment dealers maintain exchange programs for supplying to the user rebuilt engines, powershift transmissions and torque converters. These rebuilt products are carried in stock by the dealer or contractor and provide a quickly available assembly to exchange for the assembly in the machine that shows evidence of needing rebuild. The evolution of modern designs of our machines has developed the concept of "unit exchange" serviceability -- design for faster removal and reinstallation of complete transmissions, for example, so as to minimize expensive downtime.

h. Oil Sampling

One of the seminar #6 dealers described a laboratory for providing service to his customers through analyzing oil for foreign pollutants and for wear particles. The method is called atomic absorption spectro-photometry.

The objective of the laboratory is to build up an experience for certain types of machines working in certain territories and to use this technique to alert the machine owner as to when contaminants may start to build up at such rates as to provide a warning of impending breakdown. The most common metal wear particles measured include copper, iron, chromium and aluminum. Entry of dirt is found by measuring the silicon content. Other parts of the laboratory analyze the oil by conventional chemical methods to measure for unsatisfactory amounts of antifreeze, water or fuel dilution. A typical atomic absorption analyzer costs the dealer \$15,000. Equipping the entire laboratory represents a total investment in the range of \$25,000 to \$30,000. It was pointed out during seminar #6 that there are approximately 95 such laboratories in the shops of earthmoving equipment dealers throughout the world. Additionally, other dealers and some contractors are using the services of 10 or more independent laboratories. This analysis technique is very successful in forecasting impending problems and avoiding catastrophic failures of the type that destroy many parts besides the parts that failed. The technique is only successful when the oil sample is carefully drawn and preserved and good records are kept.

1. The Users

In seminar #6, two users were represented. One of these was a relatively small contractor owning 35 earthmoving machines and doing a total contract business of roughly \$2 million per year. Most of his work is done in and around the state of Kentucky. Because of the small number of machines, it is possible for this contractor to keep very good records of each machine. This contractor highlighted the importance of availability of the machine as being a prime factor in ultimate profitability and success of the business.

A measure of the utilization and conservation of materials is the ability to keep each key machine in a fleet of machines available and in good operating condition. On the other hand, unplanned downtime represents a waste of materials through idle machines, and idle key machines shut down other machines in the operation.

This user reported the following as key economic factors in his business:

- Productivity
- Availability
- Repair costs

In his analysis of the relative importance of these factors as contributors to year-end net income, he reported the following:

- 2% gain in productivity - \$27,300
- 2% gain in availability - \$27,300
- 2% reduction in repair costs - \$1,620

The significant point was that in this contractor's operation, improvements in productivity and machine availability are much more cost significant than repair costs are.

The large contractor represented was one of the half dozen largest in North America. The equipment fleet investment at original cost is \$150 million. Annual volume of contracts is \$500 million. In a typical year, there are 45 active projects.

Because of the movement of machines from job to job, the mobility of machines on a large project, and the large number of projects going on, it is extremely difficult to keep accurate downtime records on individual machines. This is true whether the downtime is planned downtime or unplanned breakdown.

It is also very difficult to keep wear rate records on components. However, both contractors agreed that repair and maintenance costs average about 4% of the total contract volume bid price.

Both contractors felt they had a good program to get the maximum practical usable wear out of individual components. They felt they were using the techniques and equipment that was available and practical for them to use.

The large contractor described two basic computer programs he has for accumulating in one central office the following:

- (1) Tire performance and tire maintenance records on earthmover size tires.
- (2) A record of the lubricant change periods for longer type fluid changes (usually those other than the engine crankcase).

2. Answers to Specific Questions Addressed in Seminar #6

The participants in seminar #6 answered those questions stated in Chapter I, Section 2(b) in regard to construction equipment. The answers to the questions follow.

Question 1 --

What are the material and economic costs of wear in the construction industry? Quantitative figures for material losses due to wear and other forms of deterioration are not available to represent the industry. The reason for this lies in the great variety of types of users, the mobility of the machines making it difficult to keep accurate maintenance records, and the fact that a considerable share of the replacement parts is supplied by independent manufacturers and by independent rebuild shops.

However, the two contractors represented agreed that their own repair and maintenance cost, not including the cost of lost production, is roughly 4% of the contract bid price.

It is also believed that the loss of production due to unscheduled downtime is a greater cost than the out-of-pocket repair expense.

Question 2 --

Are the optimum wear-control procedures being followed in the construction equipment industry? The participants of seminar #6 believed that optimum wear-control practices are generally being followed.

Question 3 --

If optimum procedures are not followed, why not? In those cases, such as with certain small-scale users, where optimum practices are not being followed the reasons lie in the lack of management control, lack of skilled labor or cost of skilled labor.

- The technology is available and the training and procedural methods are available.
- Seminar #6 participants could not suggest changes in economic or taxation practices that would result in improvement in the application of technology.

Question 4 --

Could products be made to last longer with improved application of technology?

Yes, products can be made to last longer. The participants of seminar #6 believe most of the basic technology for doing so is already known and is available to the industry. As to the cost effect, there are different answers.

Further improvements in sealing the engine, transmission, and other power train components against the entry of contaminants would usually cost somewhat more in the original manufacture but would produce an overall cost reduction to the user.

The same can be said about reliability improvements in engine installation components and other external power train components throughout the machine. Further improvements are desirable.

Concerning external parts subject to direct contact damage and abrasive wear from the material being moved, the final cost and the use of materials is highly variable, dependent on the job conditions.

There is likely to be a net cost increase and a material wastage if the manufacturer attempts to impose on all users the wear-life improvement needed only on the 5% to 10% of jobs at the severe end of the job spectrum.

A more efficient allocation of strategic materials can be made by severe-usage optional designs offered by the manufacturer, by "custom tailored" alterations offered by the dealer, or by contractor advance preparations such as plating with heat treated plate or by hard surface welding. Natural competitive cost forces tend to produce this desirable result.

Question 5 --

Is any form of life-cycle costing used with regard to the construction equipment industry? Some small-scale users can and do use life-cycle costing when their job conditions permit accurate cost records to be kept on individual machines.

Question 6 --

Does the construction equipment industry have an established wear control/reduction and costs program? The manufacturers have specific programs to reduce wear costs and loss of materials due to wear, fatigue, and other deterioration.

Dealers and users have practices that result in wear-control improvement, but do not necessarily organize a program called "wear-control".

**PART TWO: TECHNICAL PAPERS PRESENTED AT AND
CONTRIBUTED TO THE WEAR-CONTROL TECHNOLOGY
WORKSHOP**

Part two of the proceedings *contain four chapters*. Chapters III-V contain technical papers presented at the workshop during the February 23, 1976, morning, afternoon and evening session. Chapter VI contains those technical papers contributed to the workshop.

CHAPTER III

TECHNICAL PAPERS PRESENTED AT THE MORNING SESSION

A. "STATUS OF WEAR TECHNOLOGY FOR IMPROVED PRODUCT DURABILITY" BY MARSHALL B. PETERSON, WEAR SCIENCES, INC.

1. Introduction

The question of improved product durability has two parts. The first relates to improved product durability and all its ramifications. The second part relates to the question of the status of those technologies necessary to support improved product durability, for example, wear technology. The question under consideration therefore is, is wear technology strong enough to support a quantum jump in product durability? In the following sections this question is discussed in some detail and an example is given illustrating the conclusions made.

2. Failures in Mechanical Components

To begin, wear processes must be put into its proper perspective within the general category of failures as distinguished from the other means by which products lose their usefulness.

As an example, the aircraft maintenance manual lists 188 malfunctions codes -- that is, 188 different things which can go wrong with an aircraft. Twenty of these refer to malfunctions of rolling and sliding components. These can be grouped into the following six categories:

- Friction Vibrations
- Plastic Flow
- Fracture
- Seizure
- Surface Pitting and Spalling
- Wear Processes

Fracture, Flow, and Friction Vibrations are governed by materials properties and should be adequately incorporated into the design process. Although much less is

known about seizure it falls in the same category, being the result of design deficiencies in materials, lubricant supply, or thermal behavior.

Surface pitting and spalling and wear processes are the expected life-limiting malfunctions which must be extended for improved product durability. The following discussion refers to the status of wear technology; however, the same general conclusions apply to each.

3. Wear Processes

The term "wear" means different things to different people. Here, wear means the unwanted removal of material by mechanical or chemical action. It is important to understand that there are different types of wear processes. Different materials properties apply to each type and most important different solutions apply when each is found in service. These wear types based upon the method of material removal are:

adhesion	tearing
cutting	chemical reactions
corrosion	electrochemical
deformation	melting
fracture	dissolving

Adhesion wear refers to material being transferred back and forth between contacting surfaces until a particle is removed. Cutting wear is the removal of a chip by a hard particle or asperity. Corrosion wear is the removal of a surface film formed in the contact area. Deformation wear is the formation and propagation of surface cracks until a particle is removed. Fracture wear results when the stress in any part of the contact area exceeds the fracture strength. Tearing is the ripping of material particles out of the surface. The other types of wear are self explanatory and refer to rather special situations.

The question to be answered is, "If sufficient wear information is available from a research, materials development, design, and service point of view to allow any large increases in product durability, should that be the desired objective?"

4. Research

Except for a few institutions, wear research is almost nonexistent in this country. However, past research and results from other countries have isolated and identified the various processes. Each process has been studied in detail and the rate controlling factors determined. Much of the research now being carried out at the present time concerns studies of variables (materials properties, operating conditions etc.) and how they affect each wear process. Yet to come are research efforts which satisfactorily quantify the different wear processes.

Of the important wear types, deformation wear (crack propagation) has not received sufficient attention and much more research is necessary in this area.

Although improved knowledge is always beneficial and will eventually have to be undertaken, it is not now a limiting item in improved product durability -- other factors are more significant.

5. Materials Development

At the present time materials development is not a limiting item in product durability. In fact, there are more wear resistant treatments available than we know what to do with. In the Navy's Analytical Rework Program over 200 wear treatments have been identified and one of these, for example, solid film lubricants has 110 different products. Many new wear treatments have been introduced during the last few years which have great potential but are not generally used.

It should be noted, however, that most of the wear treatments are based upon high hardness which are beneficial for adhesion and cutting types of wear. Unfortunately, these are of little benefit for deformation wear processes where high toughness is required. If there is a need in the materials development area it is to develop coatings for deformation wear resistance.

6. Design

In design there will be some problems if increased durability is desired. Currently, designs are based upon experience and experience is based upon current practice.

If longer life is desired it will have to be based upon new data. This design data will have to be obtained and design techniques developed. Such information will then have to be put in a usable form so designers can use it.

7. Service

Here is another problem area. Most wear problems are not the result of poor design. Rather they result from the fact that the service conditions were not anticipated in the design or could not be adequately controlled. These service conditions in more or less order of importance are as follows:

- Contamination
- Unnecessary vibration
- Misalignment
- Excessive loads
- Insufficient lubricant

If improved wear product durability is to be obtained these conditions will have to be controlled to a greater degree. This may be accomplished in service or by designs which minimize the effect.

Secondly, to aid in the identification and solution of wear problems arising in service, better wear identification techniques will be necessary. It is very important not only to say that wear is occurring but to be able to identify the type of wear. A unique solution can then be applied for that particular problem. Research of this nature is now being carried out at Office of Naval Research (ONR) by Lt. Miller.

8. Examples

Many examples can be cited where cost reduction and improved durability were obtained by improved wear resistance. For example, in metal cutting significant improvements have been made in tool life by the use of solid films which cost very little to apply. However, it has just been in the last few years that the magnitude of the cost of wear has become apparent.

In a study conducted by a task force of the Mechanical Failures Prevention group, all of the maintenance and repair costs were analyzed for a ship's propulsion system over a period of 3.7 years. The total cost of maintenance was determined to be \$48,903,540. Of this maintenance a certain portion could be identified with a particular malfunction. These costs were as follows:

Contamination	\$8,427,694
Wear	5,759,911
Corrosion	1,265,479
Fracture	745,004
Vibration	705,268
Leaks	535,470
Misalignment	323,322
Calibration	152,822
Lubrication	193,340
Operation checks	551,132
Engine Data	742,880

Comparing the major costs on a per ship per hour basis, the following data are obtained:

Fuel Costs	\$75.00/ship/hour
Wear	38.92/ship/hour
Contamination	56.94/ship/hour
Corrosion	8.55/ship/hour

It can be seen that the wear costs are over half the fuel costs. If the wear costs which result from contamination are attributed to wear rather than contamination, that figure will increase to be almost two thirds of the fuel costs.

A further detailed review of the wear problems and their potential solutions showed that they are mostly service related and could be easily solved using existing technology. Most of the problems resulted from a few components, and their malfunction triggered other system difficulties.

The conclusions from this example have been generally confirmed by other experience with aircraft.

9. Conclusions

In general it is concluded that present wear technology would support extending product durability with two conditions:

- (1) Improved design techniques will have to be developed.
- (2) An improved understanding and control of the service conditions which lead to excessive wear will be necessary. Improved service wear identification techniques will also be necessary.

The extension of product wear life would not be expensive and could save considerable maintenance expenses based on the data analyzed for a number of applications.

The question of materials savings cannot be answered at the present time; however, high maintenance requires a large amount of parts in supply. This, too, can be considered material wastage.

B. "FACTORS CONTROLLING LONGER PRODUCT LIFE: THE CASE FOR CONSUMER DURABLES" BY W. F. FLANAGAN* AND R. T. LUND**

1. Introduction

There are many naturally-occurring incentives for increasing the life of manufactured products. A simple listing of these might include the lessening in the demand for scarce resources; the decrease in the rate of solid-waste disposal; the improvement in environmental quality as a result of the decreased industrial activity; the decreased cost to the consumer averaged over the years of product use; and the appreciable saving to the

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Portions of this paper are from a working paper "Incentives for Longer Product Life: A Case Study" prepared by R. T. Lund for the Organization for Economic Cooperation and Development, Paris, October 1975.

total economy, through the retention of the "value added" during manufacture for the products which would otherwise be reduced to scrap or waste. In order to show how these incentives manifest themselves, and what impacts might follow from their being effective, let us consider them as they apply to household consumer durables. Household consumer durables (HCD's) are particularly interesting because they represent products whose initial costs are high, whose average life expectancy is large (10 years or more), and whose continued use is strongly affected by consumer preference.

2. Requirements of the Household Appliance Industries

HCD's represent a market whose shipments are valued at \$13 billion yearly, or just under 1.0% of GNP, and one which has measurable impact in many industrial sectors. Table III-1 illustrates this by showing the direct requirements of the Household-Appliance Industry (SIC 363) for the year 1970 which were supplied by other selected industries. Because of the complexity of these products, a large fraction of the materials used in the manufacture of HCD's have a large value-added component in their cost, and this is further enhanced in the manufacturing and assembly processes (Table III-2). Consequently, the economic loss associated with product discard is large and this is illustrated by the large gap between the market value of new products and the value of the materials recovered as scrap (Table III-3). Only a few percent of the retail value is recovered by recycling materials rather than components. Table III-4 gives more highly disaggregated data on material requirements for three major products of this industry, namely: clothes washers, refrigerators, and room air conditioners. Over the years the consumption of materials by this sector has risen steadily (Figure III-1), but there has been a shift towards the use of more plastics, and a general substitution of aluminum for copper.

3. Lifetime, Durability and Reliability of HCD's

It is seen in Table III-2 that the expected average life of the appliances listed is about 12 years. If their average life could be increased to 16 years (i.e., 33%), the number of units required to satisfy the same market would decrease by 25% for every subsequent year as soon as the longer product life is achieved. This points

**TABLE III-1. *1970 DIRECT REQUIREMENTS BY THE HOUSEHOLD
APPLIANCE INDUSTRY**

Industry SIC Code	Selected Industry	Purchases by Appliance Industry in 1970 (10 ⁶ \$)	Resulting Employment in Various Industries in 1970 (10 ³ people)
307	Plastic Products	410	14
331	Blast Furnaces and Basic Steel Products	310	18
345-6	Screw Machine Products	200	15
342, 347-9, (x3491)	Other Fabricated Metal Products	210	12
358	Service Industry Machines	170	5
362	Electrical Industrial Apparatus	490	24
363	Household Appliances	54	154
371, 382, 387	Scientific and Controlling Instruments	120	150
50	Wholesale Trade	190	23
731	Advertising	190	2
73(x731)	Miscellaneous Services	38	11
Total, including All Other Industries		3700	450

*Data Compiled From:

"The Structure of the Economy in 1980 and 1985"
U. S. Department of Labor, Bureau of Labor Statistics
Bulletin 1831 (1975)

1972 Census of Manufacturers
MC 72 (2) - 36B (Jan. 1975)

The value of shipments of Household Appliances in 1970 was estimated to
be \$5.4 x 10⁹ or approximately 0.8% of GNP.

TABLE III-2. *1972 SELECTED DATA ON HOUSEHOLD APPLIANCE INDUSTRY

Industry SIC Code	Product	# Units Produced (10 ⁶)	Material Costs (10 ⁶ \$)	Retail Value (10 ⁶ \$)	Average Life (yrs)
35856 31-69	Room Air Conditioners	4.5	} 240	910	12
11	Dehumidifiers	0.5		38	
36321 00	Refrigerators	6.3	840	1700	20-15
36331 31	Washing Machines (auto)	4.8	} 670	1200	11
36	(wringer)	0.3		45	
51	Dryers (gas)	0.9		180	13
55	(electric)	3.0		510	
36394 12	Dishwashers (portable)	0.8		160	
14	(built-in)	2.3	160	510	10
17	Disposals	2.7		170	

*Data Compiled From:

Merchandizing Weekly, Feb. 25, 1974.

1972 Census of Manufacturers, MC 72 (2) - 36B (Jan. 1975)

M.I.T., Center for Policy Alternatives, The Productivity of Servicing Consumer Durable Products, Cambridge, Mass., (June 1974)

Pennock, Jean L. and Carol M. Jaeger, "The Household Service Life of Durable Goods," Journal of Home Economics, (Jan. 1964)

Ruffin, M. D. and K. S. Tippet, "Service-Life Expectancy of Household Appliances: New Estimates from the USDA, Home Economics Research Journal, (March 1975)

TABLE III-3. SCRAP MATERIALS VALUES VS. PRODUCT MARKET VALUES

Item	Average Weight	Retail Value (New)	Scrap Material Value*	Percent of Retail Value
Cooking Range	200 lb. (90 kg.)	\$300	\$2.88 ^(a)	0.96%
Refrigerator	325 lb. (148 kg.)	\$450	\$8.75 ^(a)	1.94%
Dishwasher	147 lb. (67 kg.)	\$275	\$3.50 ^(a)	1.27%
Clothes Washer	250 lb. (114 kg.)	\$275	\$5.92 ^(a)	2.15%
Clothes Dryer	145 lb. (66 kg.)	\$175	\$2.72 ^(a)	1.55%
Beer bottle (empty)	6.5 oz. (184 g.)	\$.032	\$.0024 ^(a)	7.5%
Automobile	3700 lb. (1682 kg.)	\$4000.00	\$60.00 ^(b)	1.5%

*Based on material content. Recovery processing costs not deducted.

Sources: (a) Sullivan, et al 1973.

(b) Based on materials weights given in Harwood (1974).

TABLE III-4a. CLOTHES WASHERS

An estimated 5.39 million clothes washers were manufactured in 1975. Here's what it took to make them:

Components and Materials	Quantity Per Unit	Total Quantity to be Consumed
Aluminum	10 lb	26,950 ton
Brass	0.5 lb	1,348 ton
Plastic	13 lb	35,035 ton
Steel	105 lb	282,975 ton
Belts, drive	2 ft	2,042 mi
Brakes	1	5,390,000
Die castings	22	118,580,000
Gasketing, rubber	2 lb	5,390 ton
Gears	5	26,950,000
Hose, plastic	7 ft	7,146 mi
Hose, rubber	16 ft	16,334 mi
Knobs	2	10,780,000
Pumps	1	5,390,000
Seals	4	21,560,000
Tubing	5 ft	5,104 mi
Valves, water	1	5,390,000
Connectors, electrical	6	32,340,000
Cord, electrical	5.5 ft	5,615 mi
Motors	1	5,390,000
Relays	1	5,390,000
Sensors	1	5,390,000
Solenoids	1	5,390,000
Switches	5	26,950,000
Timers	1	5,390,000
Wire, electrical	95 ft	96,982
Fasteners	180	970,200,000
Labels/nameplates	3	16,170,000
Paint	0.5 gal	2,695,000
Porcelain enamel	60 sq ft	11.6 sq mi
Adhesive tape	4 ft	4,084 mi
Corrugated fiberboard	150 sq ft	29 sq mi

Source: Appliance Manufacturer, January 1975

TABLE III-4b. REFRIGERATORS

An estimated 6.12 million refrigerators were manufactured in 1975. Here's what it took to make them:

Components and Materials	Quantity Per Unit	Total Quantity to be Consumed
Aluminum	3.4 lb	10,404 ton
Copper	1.25 lb	3,825 ton
Gasketing	3.25 lb	9,945 ton
Insulation	5.85 lb	17,901 ton
Plastic	49.4 lb	151,164 ton
Steel	154.5 lb	472,770 ton
Tubing	23 ft	26,660 mi
Wire, rack	144.6 ft	167,610 mi
Compressors	1	6,120,000
Fans/blowers	1	6,120,000
Knobs	2	12,240,000
Connectors, electrical	3	18,360,000
Cord, electrical	6 ft	6,955 mi
Motors	1	6,120,000
Relays	1	6,120,000
Switches	1	6,120,000
Thermostats	1	6,120,000
Timers	1	6,120,000
Wire, electrical	34.5 ft	39,990 mi
Adhesives	0.2 lb	612 ton
Fasteners	203	1,242,360,000
Labels/nameplates	7	42,840,000
Refrigerant	0.5 lb	1,530 ton
Paint	0.17 gal	1,040,400 gal
Porcelain enamel	34 sq ft	7.5 sq mi
Adhesive tape	33.5 ft	38,831 mi
Corrugated fiberboard	101.4 sq ft	22 sq mi
Steel binding, strap	17 ft	19,705 mi

Source: Appliance Manufacturer, January 1975

TABLE III-4c. ROOM AIR CONDITIONERS

An estimated 3.13 million room air conditioners were manufactured in 1975. Here's what it took to make them:

Components and Materials	Quantity Per Unit	Total Quantity to be Consumed
Aluminum	18.4 lb	28,796 ton
Copper	4.1 lb	6,417 ton
Insulation	0.24 lb	376 ton
Plastic	10.8 lb	16,902 ton
Steel	49.2 lb	76,998 ton
Compressors	1	3,130,000
Fans/Blowers	2	6,260,000
Gasketing	0.14 lb	219 ton
Knobs	2	12,520,000
Refrigerant	2.2 lb	3,443 ton
Tubing	181.3 ft	107,479 mi
Connectors, electrical	9	28,170,000
Cord, electrical	5.9 ft	3,498 mi
Motors	1	3,130,000
Switches	1.5	4,695,000
Thermostats	1	3,130,000
Wire, electrical	9.6 ft	5,691 mi
Adhesives	0.2 lb	313 ton
Adhesive tape	5.6 ft	3,320 mi
Fasteners	85	266,050,000
Labels/nameplates	9.5	29,735,000
Paint	0.1 gal	313,000 gal
Corrugated Fiberboard	30 sq ft	3.4 sq mi
Steel binding, strap	15.5 ft	9,189 mi

Source: Appliance Manufacturer, January 1975

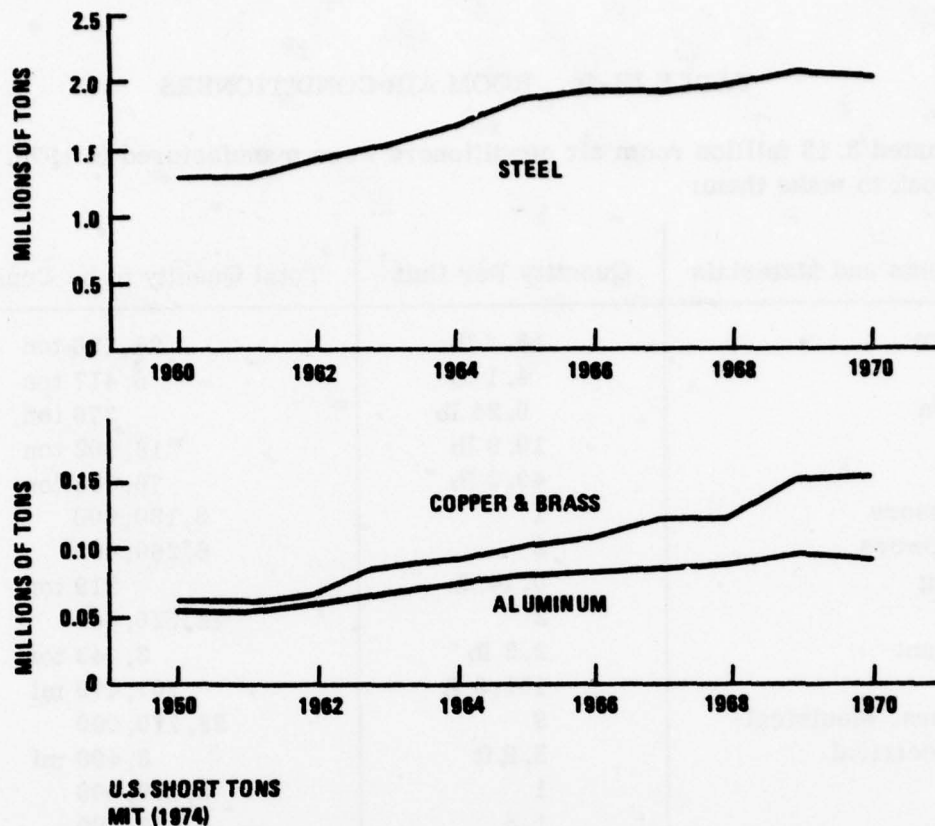


Figure III-1. Tonnage of steel, copper and brass, and aluminum used for six major household appliances.

out that a delay time is required before the impact of "added life" can be felt, and also that additional material costs to achieve this "added life" should be less than the future-discounted material savings.

It is important to understand that product "life" is a statistical concept. For a given year of manufacture some products are discarded during their first year of use, for a variety of reasons. The number discarded per year generally rises with age, peaking at a point somewhat beyond the average life of all of the sets of that product year, and then quickly dropping to zero with increasing age. This is illustrated in Figure III-2 for new color television sets. The average life expectancy (the average of all the predicted lives) is 12 years, at which time approximately 60% of the sets produced today would still be in use. The median life (when only 50% of the sets survive) would be almost 14 years.

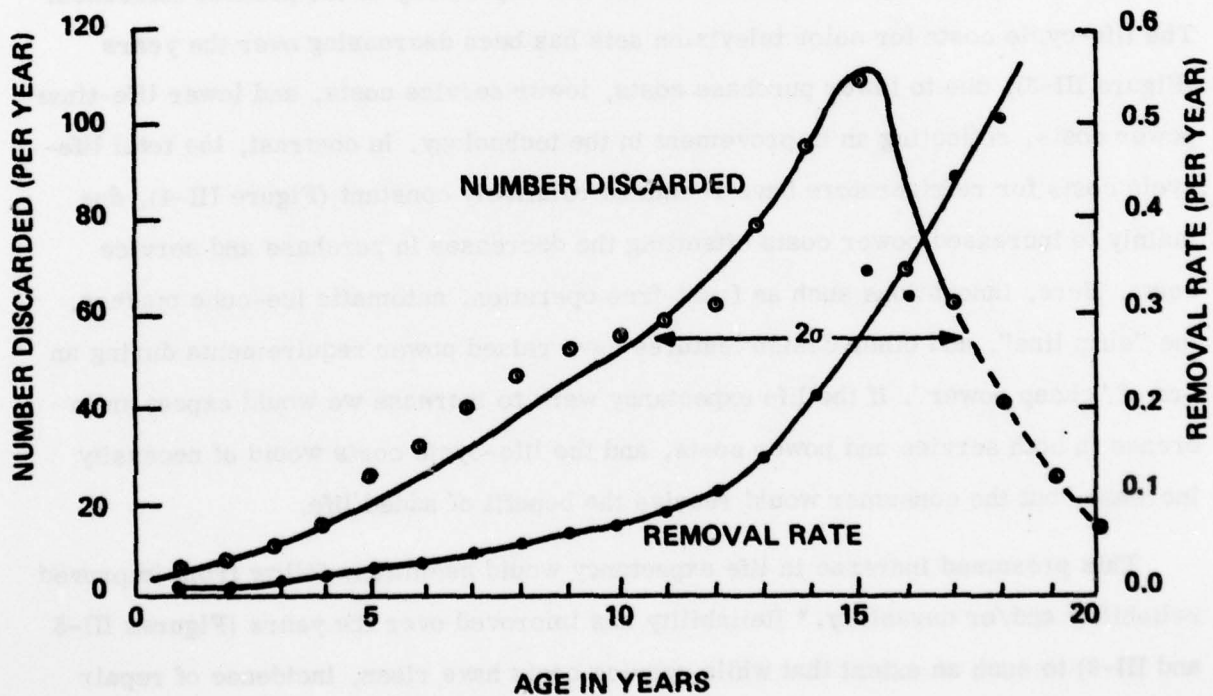
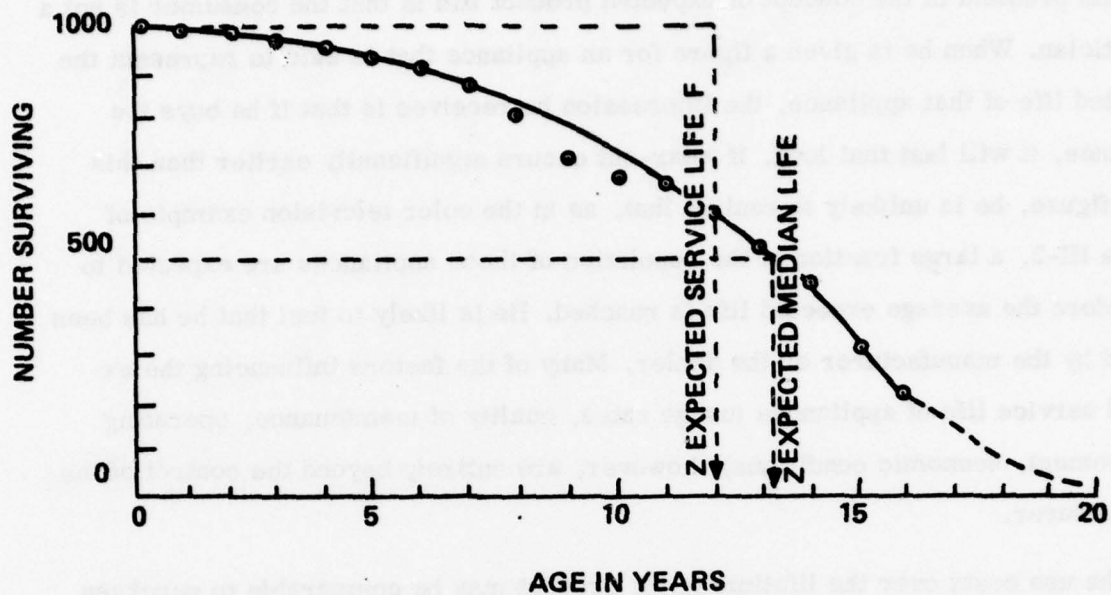


Figure III-2. Prediction of the number of color TV sets purchased new surviving in an original population of 1000, with the related removal rate and yearly number of discards. First-owner experience only. (after Ruffin and Tippet, 1975).

One problem in the concept of expected product life is that the consumer is not a statistician. When he is given a figure for an appliance that is said to represent the expected life of that appliance, the impression he receives is that if he buys the appliance, it will last that long. If wear-out occurs significantly earlier than this given figure, he is unlikely to realize that, as in the color television example of Figure III-2, a large fraction of the population of those appliances are expected to fail before the average expected life is reached. He is likely to feel that he has been misled by the manufacturer or the dealer. Many of the factors influencing the expected service life of appliances (usage rates, quality of maintenance, operating environment, economic conditions), however, are entirely beyond the control of the manufacturer.

The use costs over the lifetime of the product may be comparable to purchase costs. This becomes more important as the life expectancy of the product increases. The life-cycle costs for color television sets has been decreasing over the years (Figure III-3), due to lower purchase costs, lower service costs, and lower life-time power costs, reflecting an improvement in the technology. In contrast, the total life-cycle costs for refrigerators have remained relatively constant (Figure III-4), due mainly to increased power costs offsetting the decreases in purchase and service costs. Here, innovations such as frost-free operation, automatic ice-cube makers, the "slim line", and other design features have raised power requirements during an era of "cheap power". If the life expectancy were to increase we would expect an increase in both service and power costs, and the life-cycle costs would of necessity increase, but the consumer would receive the benefit of added life.

This presumed increase in life expectancy would seemingly follow from improved reliability and/or durability. * Reliability has improved over the years (Figures III-5 and III-6) to such an extent that while service costs have risen, incidence of repair has decreased sufficiently to offer an overall decrease in life-cycle costs (Figure III-7).

*Here reliability is taken to be inversely proportional to the incidence of repair, while durability is taken to be a measure of potential useful life (as opposed to "actual" life, which may be shortened by early discard, whatever the reason).

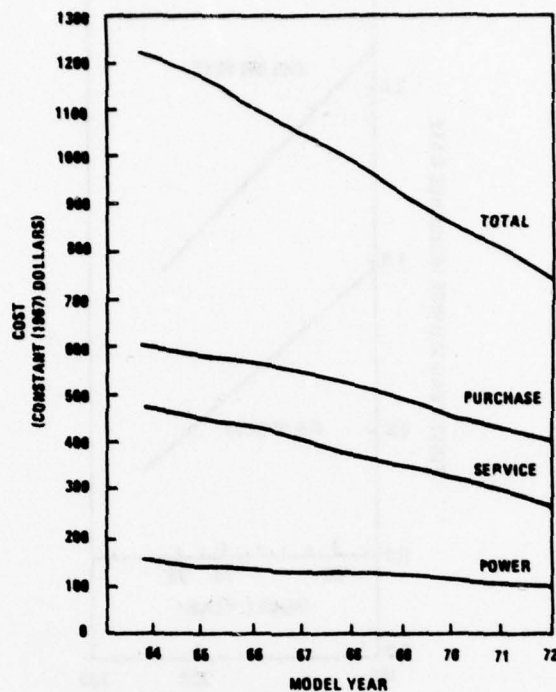


Figure III-3. Trends in color television life-cycle cost, discounted to present value at time of purchase and deflated to constant dollars.

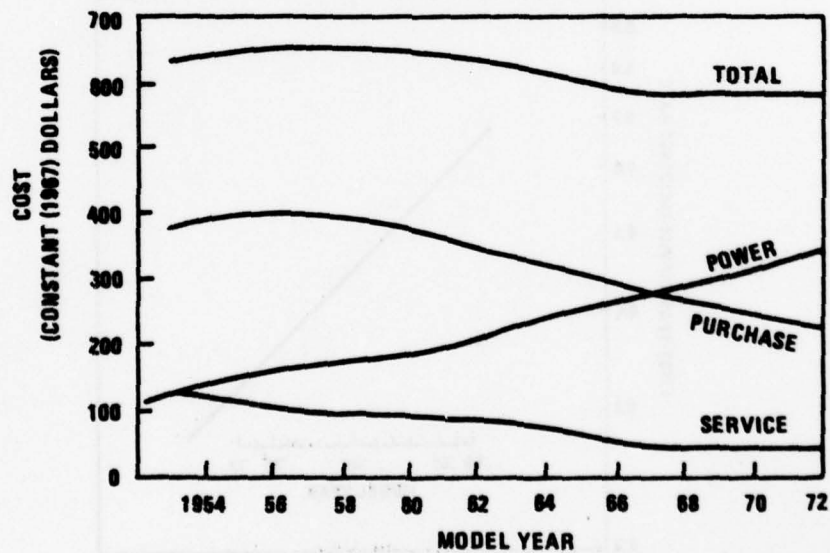


Figure III-4. Trends in refrigerator life-cycle cost, discounted to present value at time of purchase and deflated to constant dollars.

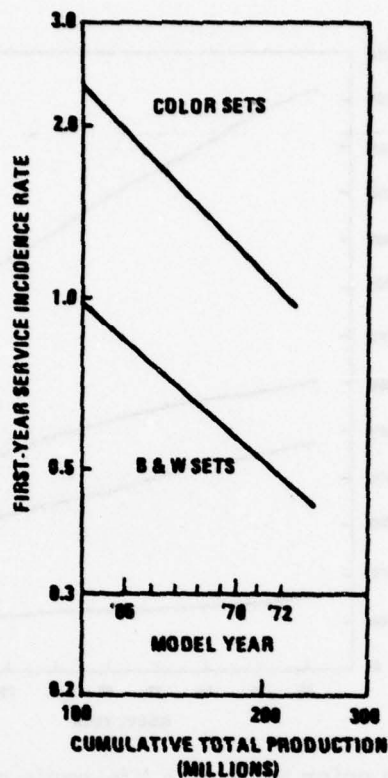


Figure III-5. First-year service-incidence rate for television sets.

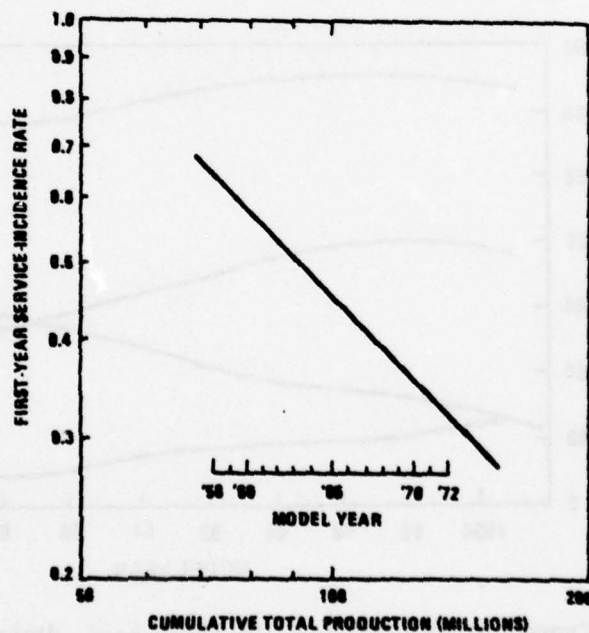
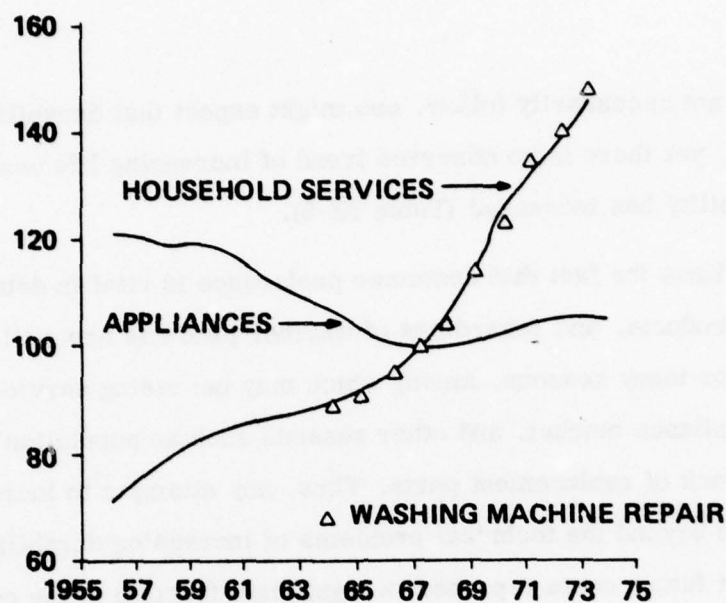


Figure III-6. First-year service-incidence rate for refrigerators.



SOURCE: U.S. BUREAU OF LABOR STATISTICS

Figure III-7. Cost Indexes for Appliances, Household Services and Washing Machine Repair

TABLE III-5. NEW APPLIANCE SERVICE LIFE IN YEARS

Product	1957-61* Dept. of Agriculture (a)	1970* Manufacturer (b)	1972* Dept. of Agriculture (c)
Room air conditioners	--	12	--
Ranges - electric	} 16	16	12
- gas		16	13
Freezers	15	18	20
Refrigerators	16	15	15
Dishwashers	--	10	11
Clothes washers	10-11	10	11
Clothes dryers - electric	} 14	12	14
- gas		12	13
TV sets - black & white	11	--	11
- color	--	--	12

*Date of data

Sources: (a) Pennock and Jaeger (1964); (b) MIT (1974);
(c) Ruffin and Tippet (1975).

Though it does not necessarily follow, one might expect that durability would increase with reliability, yet there is no observed trend of increasing life over the same time span that reliability has increased (Table III-5).

This underlines the fact that customer preference is vital in determining the life expectancy of products, and regardless of whether products are still functional, they are discarded for many reasons, among which may be: rising service costs, affluence, a weak used-appliance market, and other reasons such as population mobility, appearance, and lack of replacement parts. Thus, any attempts to increase life expectancy would have to go beyond the technical problems of increasing durability, and deal with this issue. Most future costs represent a significant fraction of the consumers' total cost even when these are discounted to present values; however, consumers discount future costs heavily, and if national conservation goals reflect future costs, consumer behavior may run counter to these goals.

4. Total System Assessment and Policy Implications

In considering policies that effect product life one must consider the total system from concept through manufacture, use, and discard, along with all of the exogenous variables which effect these processes (Figure III-8). In this way the many pressure points become explicit, and it is easily understood that the impacts of any policy are different for different sectors of the system. This justifies an expenditure of effort to involve necessarily all of the affected "publics" in the process of evaluating impacts of policy, and it is not surprising to find that such involvement is sought by the Office of Technology Assessment in its assessment of "materials conservation through less wastage". It follows from the foregoing that resource demand, solid waste disposal, and pollution would be expected to decrease with increased product life, but there are also some disadvantages to be considered. Some feel that innovation would be stifled, or at least delayed. The decreased demand for products would cause an economic decline which would be partially, if not wholly, offset by the flow of the money saved to other markets (*higher standard of living?*). The timing of the policy is also important, for example such an economic decline in the household consumer durables sector would

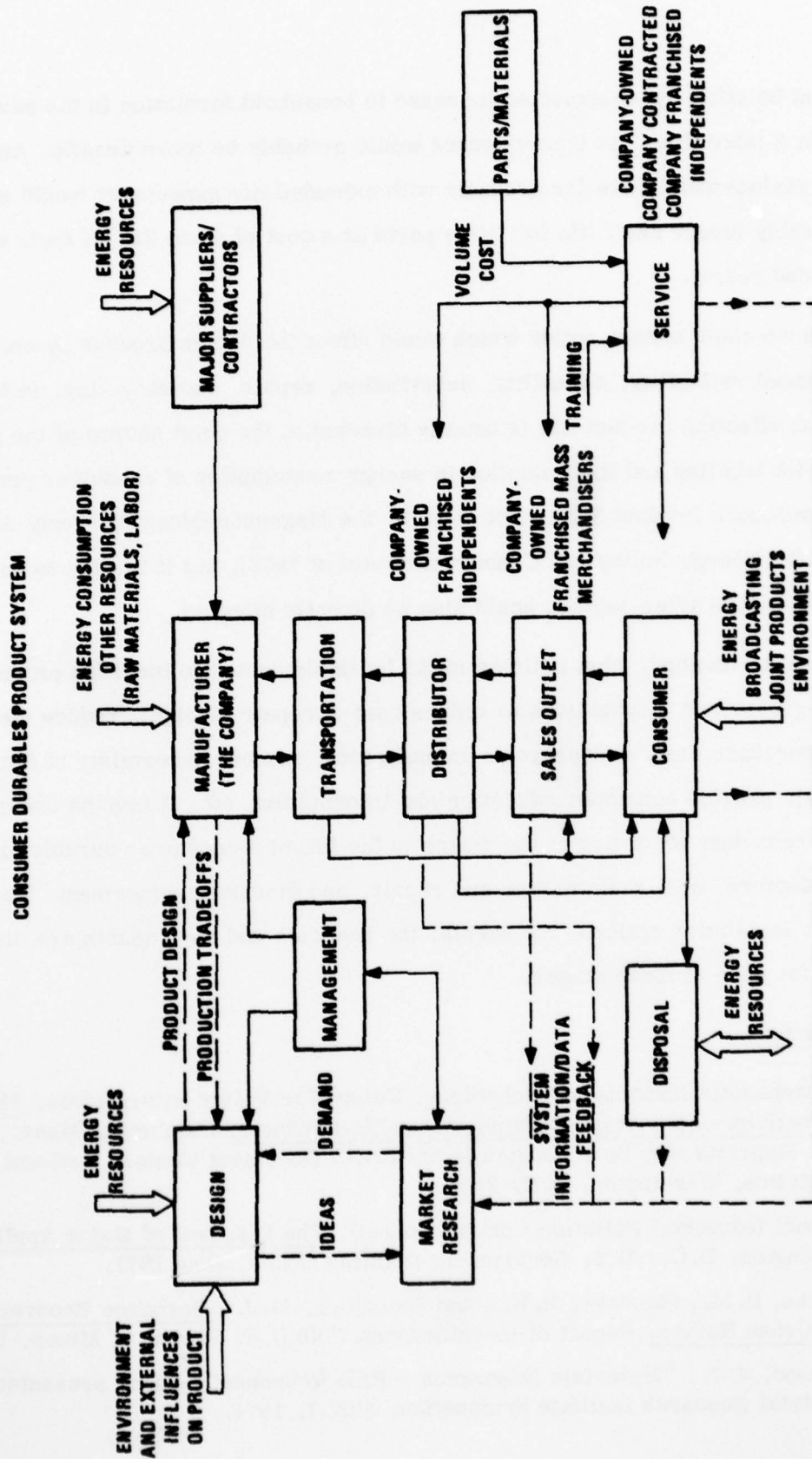


Figure III-8. Consumer Durables Product System

at present be offset by an expected increase in household formation in the next five years. At a later time, its consequences would probably be more drastic. Any effort to stock replacement parts for products with extended life expectancy would require a comparably larger shelf life for these parts at a cost of about 20% of their value compounded yearly.

Thus we could assess policy which would affect the design process by encouraging increased reliability, durability, substitution, repair, and recycling. In fact, legislation affecting product life is usually directed at the point source of the product, dealing with labeling and the reduction in energy consumption of consumer products (e.g., Consumer Product Safety Act of 1972, the Magnuson-Moss Warranty Act of 1975 and the Energy Policy and Conservation Act of 1975), but it is easy to envisage ways in which the other sectors could also be directly affected.

Beyond technology, what policies might be implemented to increase product life? These might include mechanisms to reduce cost of repair (design), reduce the ratio of service/purchase cost, encourage re-manufacture, remove uncertainty of future costs (warranty), provide consumer education and information, etc. It may be useful to consider remedies according to the stages in the life of a consumer durable; design and manufacture, use, maintenance and repair, and discard/replacement. The regulatory or legislative options, the agents, the agencies and the impacts are distinctly different for each of these stages.

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C. "NEW MANUFACTURING TECHNOLOGY FOR MATERIALS CONSERVATION"
BY ROBERT E. MATT, AEROJET GENERAL

Wear has a dual personality. To many it is simply increased performance or longer life. Wear, however, can either be "CONTROLLED" or "UNCONTROLLED".

Increased performance or longer life are the units of measure of uncontrolled wear. The units expressed as a percentage value, relate to material or equipment usage, and consequently to material conservation. Controlled wear, the more direct approach to material conservation, is indicated by new manufacturing technology. Its unit of measure is the ability to produce parts or equipment utilizing lower cost or lesser quantities of raw material. It may or may not be accompanied by benefits in uncontrolled wear.

Significant advancements in manufacturing technology have occurred in recent years, including the substitution of plastics for metal, the development of composite materials and powder metallurgy. It is the latter subject that is of concern in this analysis of conservation of materials through controlled wear.

Powder metallurgy is not new but until the last 10 to 15 years, has been considered a low technology industry. The Air Force has been the stimulant with their requirement for increased performance engines at hopefully reduced costs. The approach currently emphasized is the production of near-net-shapes for forging. The basis for their efforts is the controlled wear of superalloy engine components.

The current superalloy requirement for Aerospace applications is estimated at 30,000,000 pounds per year, of which 50% is estimated to be used in the production of large components such as turbine discs. The following is a cost breakdown of a conventionally forged Inco 718 turbine disc:

Basic Metal	20%
Melting	2%

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NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA

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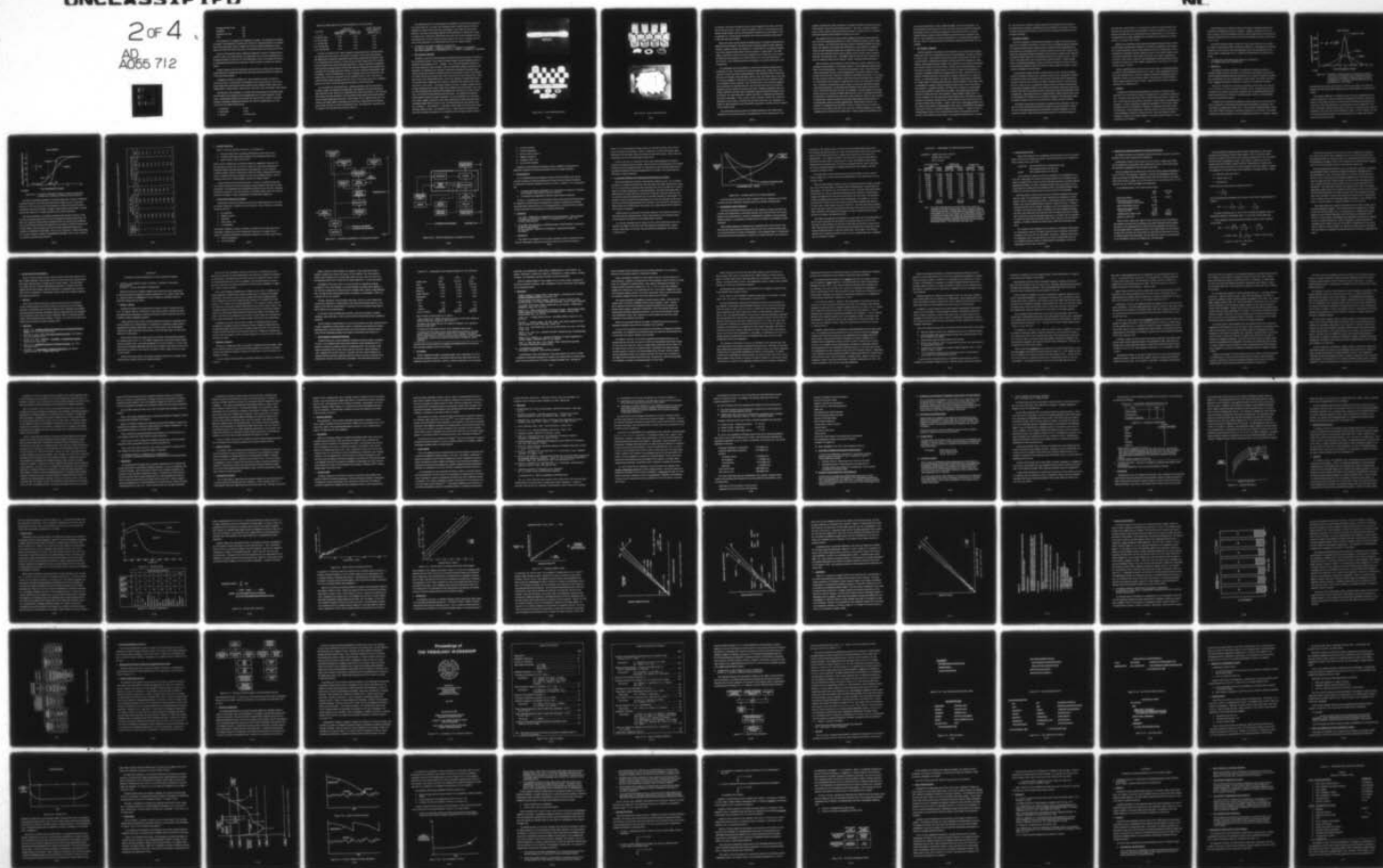
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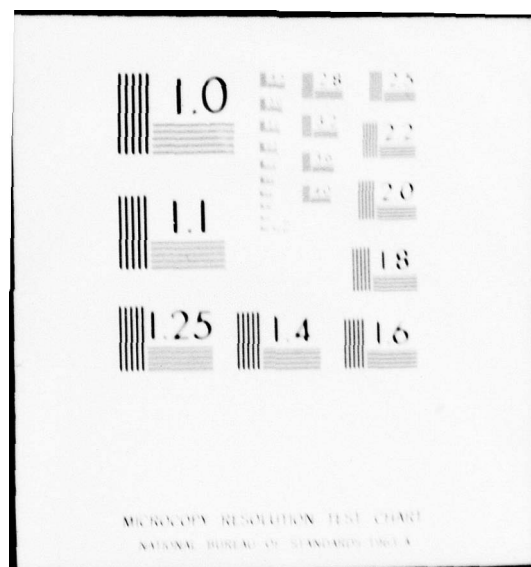
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Forging and Heat Treat	11%
Machining	54%
Inspection and Test	11%
Misc.	2%

This example is of a finished part weighing 15.5 pounds. The starting billet weighed 235 pounds. Approximately 200 pounds were removed in rough machining at an estimated cost of \$5.00 per pound, and 19.5 pounds were removed in final machining at an estimated cost of \$15.00 to \$20.00 per pound. The finished product was valued at \$4,500.00.

The use of hot isostatic powder metallurgy techniques to produce a forging preform allowed the disc to be produced from a 45 pound blank. The cost of the subsequent disc, including machining, was \$2,000.00. This represents a direct cost savings of \$2,500.00 in machining and materials plus a long term, indirect savings in machine tool requirements.

Another example of powder metallurgy controlled wear is evident in the production of high speed steel cutting tools which have been cold pressed and sintered to shape and 100% of theoretical density.

Although the concept of pressing P.M. parts to shape is not new, the ability to produce precision, complex parts of 100% density from complex alloys is. Some of the parts (Figure III-8A and Figure III-8B) produced by this technique include spade drills, milling cutters, thread chasers, pipe reamers, end mills, hobs, hex punches, and broaches.

The objective of the technique is to produce parts matching the semi-finished shape and tolerances of the cutting tool in its configuration prior to heat treatment. In some cases, supplemental machine tool operations are required while in others, only finish grinding. Acceptable dimensional tolerances vary with the configuration but in most cases follow the schedule shown below:

1" dimensions	± 0.010
2" dimensions	± 0.015
3" and over	± 0.005 per inch.

Material savings range from 30 to 60% depending on the part produced.

Tool Type	Commercial Machine Tool, lb.		Powder Metallurgy Parts to Shape, lb. Sintered Tool
	Rough Stock	Finished Tool	
4" dia Mill Cutter	16.54	8.50	8.50
1.5" dia End Mill	2.88	1.57	1.57
1.0" dia End Mill	1.23	0.76	0.76
0.75" dia End Mill	0.61	0.25	0.25
0.375" dia End Mill	0.30	0.11	0.11

In terms of controlled wear, these savings are substantial and for materials which cost typically \$2.50 per pound, allows plenty of margin for new product development. The significance in material conservation arises in the analysis that the already proven P. M. technology has as its goal a 113,335 net ton tool steel market (AISI 1974) of which 30,000 net tons are the more costly high speed steels. Using a conservative estimation; if this particular process enjoys a 40% average material savings and can be applied to an immediate 5% of the high speed steel market, it will have conserved an estimated 6 tons of vanadium, 24 tons of molybdenum, 24 tons of tungsten and 30 tons of chromium. The market value of the steel conserved would be estimated at \$3,000,000. This does not include the other metals making up this alloy class or other alloy steels such as stainless steel nor the cost of tooling and equipment necessary to produce the parts.

In an evaluation of uncontrolled wear, cutting performance has been evaluated in drilling, milling, and single point cutting tests. Performance in all cases has been at least equivalent to the commercial counterpart and in most cases superior. The improved performance was best indicated in tools with shallow edge support and in applications of impact loading during interrupted cuts. In the instance of 3/8" jobbers drills, the P. M. material was found capable of operating at an 18% faster cutting speed for drilling the same number of holes. In terms of uncontrolled wear, this means that 4 machines could be utilized to do a job that would normally require 5.

The potential of the P.M. developments are significant in terms of both controlled and uncontrolled wear. Currently, the sintering of parts to shape has been limited to cutting tools. Future efforts may focus on bearings or other high load requirement hardware. Only minor development efforts would be necessary to advance the concept to stainless steel. Superalloys and titanium alloys have not yet been considered but the concepts involved are basic; hence they should apply to any metal. Eventually they may even include producing a 15.5 pound turbine disc from 15.5 pounds of metal.

D. "ECONOMIC FACTORS IN PRODUCT DURABILITY"

BY CARL M. MADDEN -- CHIEF ECONOMIST, CHAMBER OF COMMERCE

REMARKS PRESENTED AT WORKSHOP BY R.S. LANDRY, CHAMBER OF COMMERCE

1. The Consumer Viewpoint

Durability is only one of several factors influencing the final consumer's decision to buy a particular product. If we consider the whole range of durable consumer goods, including the most expensive of all -- housing -- it is clear that frequently durability is low on the consumer's scale of values. The most noteworthy example of this fact is the automobile. If consumers were primarily concerned with automobile durability they would be much more inclined to purchase Jeeps or the consumer version of the Checker Cab rather than the more stylish autos with various deluxe comfort features that, in the past at least, have captured their fancy. In fact, the consumer's marked high interest in automobile style, appearance and comfort is evidenced by the short period of time -- some three or four years -- of average retention of an auto. It might be argued that the average retention period would be longer if the machine were more durable. But to support this proposition the exceptions to the general rule would have to be cited. Exceptions, such as the Mercedes Benz and the Rolls Royce, are expensive automobiles whose expense reflects the larger investment, not only in durability but in machines that require a higher proportion of labor than production-line models and whose style and design change little from year to year. In these instances the snob appeal of the more expensive -- and distinctive -- Mercedes or Rolls appears to be the major factor affecting consumer choice, not durability per se. A better test for measuring more precisely the relative importance of car durability to the average car buyer would be

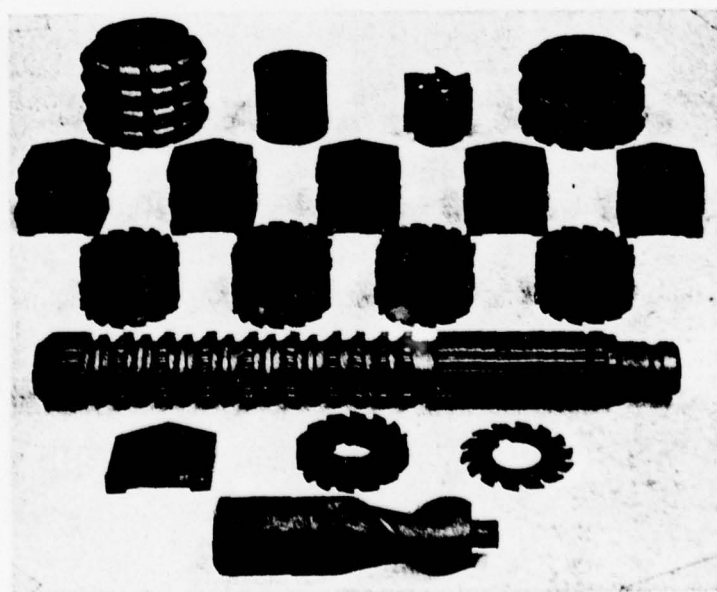
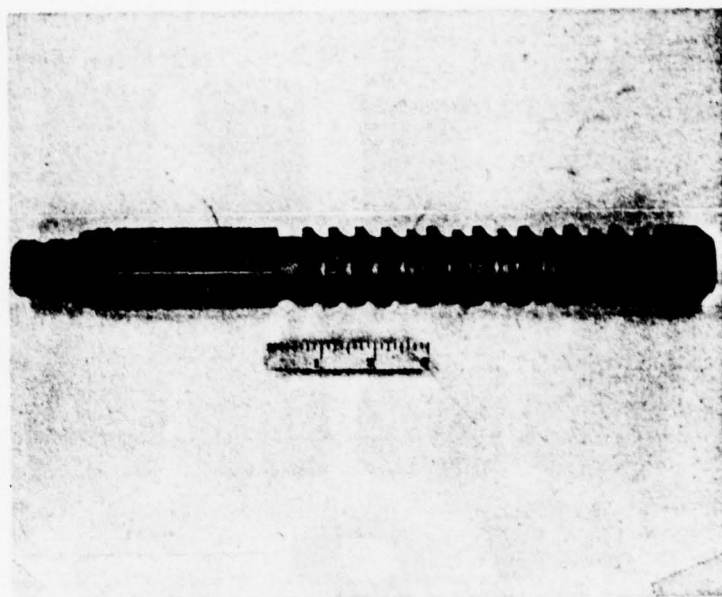


Figure III-8A. Powder Metallurgy Parts

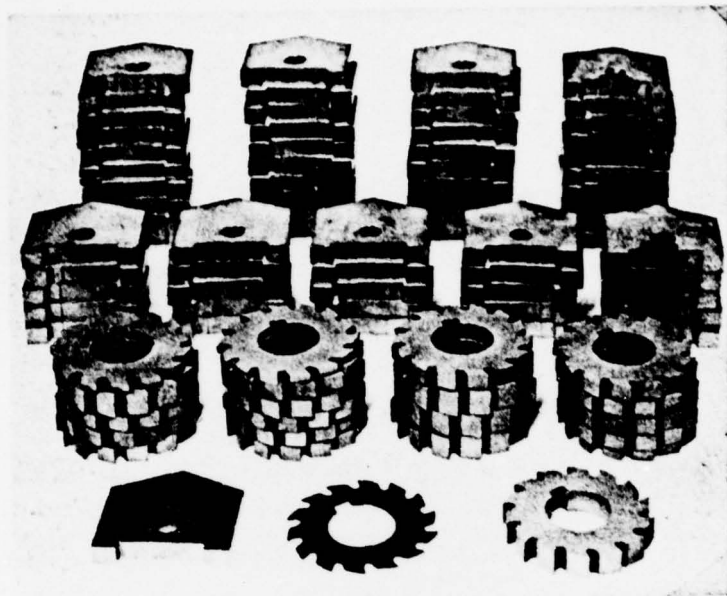


Figure III-8B. Powder Metallurgy Parts

for Detroit to build more durability and fewer style changes into its autos, and watch sales of the new models. This is unlikely to happen, however, in the present circumstances of high energy costs and environmentally imposed costs on the industry. This is especially so, because greater durability under existing technology means greater weight and poorer gas mileage.

Recent auto sales reports indicate the shifting nature of consumer preferences for different sizes and models. Now that the price of gasoline appears to have stabilized and gas is readily available, the consumer is concentrating his car buying on medium-sized, fully equipped models rather than sub-compacts or large models. This shift might be construed as a desire for more durability but only indirectly, since a larger and somewhat more expensive car (without extras) is not only more durable but is also roomier, more comfortable and more prestigious, all qualities that appeal to the average buyer.

It is undoubtedly true that durability is a much more important consideration in housing than in autos. But this does not mean necessarily that a larger share of the consumer's outlay represents housing durability. The installment method of financing both autos and housing, along with higher interest rates, has caused interest payments on a 30 year mortgage to represent more than one-third of the total consumer outlay if the mortgage is held to maturity. Also, the high turnover rate of houses suggests a lower preference for durability than was true in the pre-World War II era when the population was less mobile and incomes were lower. Probably durability is most important in general to the final buyer of basically utilitarian household equipment such as furnaces, air conditioning units, washers and dryers, refrigerators and freezers and certain furnishings -- rugs, carpets, clocks, draperies, and the like. Electronic equipment, such as radios, television sets and home stereo and movie equipment, is subject to rapid obsolescence and lies therefore somewhere in-between the two extremes on the durability scale.

The trend toward numerous built-in household appliances in the modern home, including several already mentioned, plus dishwashers and food disposal units, has

probably increased the relative importance of appliance durability, because such equipment becomes a part of the most durable product -- the house. In heavily urbanized areas, in fact, realtors advise home sellers to repair or replace all worn or defective household equipment before putting the property up for sale.

The examples that I have cited certainly suggest that extreme caution should be used in heavily emphasizing durability as a factor influencing consumer choice. Quite to the contrary, as we know from numerous surveys of consumer attitudes and buying habits, the consumer is bombarded and influenced by a large number of competing pressures that marketing analysts have recognized for many years. Examples run from the most pedestrian factors such as relative prices, income, ease of access to financing, and financing terms, to the highly subjective and less easily measured aspects of consumer choice such as comfort, styling, convenience and performance.

Since the theme of this workshop is less wasteful use of scarce materials, I am reminded in this connection of an economic study on "Unused Resources and Economic Waste" by David Rockefeller -- his doctoral dissertation, in fact. The principal conclusion of this study was that, far from being simple, the notion of waste is a complicated one that involves subjective evaluations by individuals and groups. For example, the idea of waste is basically parallel to the idea of scarcity and higher price. Scarcity is an idea that has been around for a long time and in fact, lies at the heart of Economics. Yesterday's economizing is today's waste, as the recent escalation of energy costs has demonstrated. Oil and natural gas displaced coal as major sources in the 1940's, 50's and 60's because coal was more expensive. Now the situation is reversed and the prices of oil and gas are higher than the price of coal, so demand for the latter has increased. If resources were not scarce there would be no need for a price system to indicate their relative scarcities and to assist both producers and consumers in allocating these resources among competing uses. When viewed in this way, the question of increasing product durability in order to conserve the use of certain resources in short supply at the time is on a par with a reduced demand for any product resulting from an increase in the product price. If other product characteristics such

as styling are minimized in order to offset the higher cost of more durability, consumer demand for the product will also be less if the particular mixture of durability and styling is not the one that most consumers of the product desire. In a market oriented economy, greater product durability cannot be forced on consumers in an effort to reduce demands on resources that happen to be in relatively short supply at the time. Only in a controlled economy would this be possible and even there it is improbable.

2. The Producer Viewpoint

Like the consumer, the producer views durability as only one of several product dimensions. Since he is constrained by total cost considerations, the typical producer will have to reduce cost outlays on some other product characteristic in order to increase durability. Building more durability into the product will increase its capital intensity. Increasing the capital intensity will increase the cost of capital incorporated in the product relative to the cost of labor. With the price of his product given, only if the price of capital is reduced relative to the price of labor will the producer be motivated to substitute durability-increasing capital for labor. This will be true regardless of whether the buyer of his product is another business firm or a final consumer. As I mentioned earlier, the buyer of a consumer durable good is influenced by a large number of considerations other than product durability. If the product price is unchanged the consumer would presumably be happy to have more of all product characteristics, including durability, but if the price is raised to cover the higher cost of more durability, product sales may suffer. The business firm that buys a producer's durable good will react similarly to being charged a higher price. Of course, durability is a more important product characteristic in the typical producer good than in the typical consumer good, but the question at issue is the same for the producer of either kind of product -- namely, will it pay to build more durability into the product at the expense of building less of other product characteristics that appeal to the buyer? This is a competitive question for the producer -- similar in scope to building greater safety or less environmentally harmful characteristics into the product. Governmentally imposed safety or environmental standards have increased

the costs and prices of affected consumer goods and have affected sales adversely to the extent that less expensive substitutes have been available in the market. The same reduction in sales could be expected as the result of a government-mandated increase in product durability.

3. The Social Viewpoint

The social viewpoint on more product durability as a means of conserving scarce resources is embodied in the public's collective choices through government programs. The essential contrast between business and government has been traditionally that each maximizes something different: business maximizes total private consumer satisfaction by producing the kinds and quantities of products that consumers have indicated through the market system they as individuals desire most at specific prices. Government, on the other hand, tries to maximize the "general welfare", mainly through income-redistributing spending for health, education and welfare and public services. Also government programs result from political voting, unlike the economic voting of consumer spending in the marketplace.

So government operates through a market system of sorts, but not according to ordinary competitive market forces. Because of its great size, government competes successfully with private consumers for the output of business and with business for productive resources such as labor and capital, using tax monies or borrowed funds. Moreover, there are as yet no generally accepted social cost-benefit measurements for government programs similar to the private cost-benefit comparisons made by the millions every day in the market economy by individual consumers and business firms. Consequently, a government decision to require greater product durability than would be determined by free market forces would have to depend on altering market supply and demand enough to achieve the social objective of greater product durability.

If the public accepts the social objective of greater product durability, there are only a few ways of achieving this objective through the private enterprise economy. One way is through setting minimum performance or product standards, as in the instances of product safety and environmental protection. With the development of

case histories of these efforts, it is becoming clear that some standards have been arbitrarily set and even have been frustrated by consumer resistance, as in the instance of auto seat belts or by unexpected adverse consequences, as in the instance of proposed EPA air quality standards that would effectively prohibit new economic activity in vast areas of the country.

Another way of achieving social objectives through the market economy would be for government and business to operate in a consortium arrangement, like Comsat, with a joint directorate. But the Comsat example may not be a useful guide to firms producing for established consumer markets, because of the conflict between private cost-benefit comparisons in such markets and public cost-benefit comparisons in markets for public goods. Moreover, the international telecommunications satellite operated by Comsat is more like a highly regulated public utility than it is a private consumer good or service.

Finally, government could revert to the New Deal device of cartelizing industry, as under the National Industrial Recovery Act. Such a cartel arrangement would require each business firm to conform to industry-established and industry-enforced standards of output, price and product quality. This approach would necessitate a radical change in national economic policy, especially the free-market orientation expressed in our antitrust laws.

4. Summary

A proposal to increase product durability as a means of conserving scarce materials is on a par with any proposal to change the mix of a product's characteristics. Proposals of this nature have both cost and demand implications. On the cost side, if the market for the product is competitive, with average cost equalling price, producers, in order to keep their average cost unchanged, will be forced to offset the higher cost of more durability by reducing or eliminating some other product characteristics. On the demand side, if the new mixture of product characteristics is less appealing to consumers at the given price, sales and profits will suffer. Therefore, producers will resist proposals to increase product durability so long as consumers do not demand it.

If government tries to influence producers' decisions in industries using scarce materials by mandating more product durability, consumer resistance will still remain a problem. And if the substitute products to which consumers turn use appreciable amounts of substitutes for the scarce resources the substitute resources could become scarce in turn.

The point of the whole matter of scarcity is that in most cases the price system will adjust to the different relative scarcities of products or raw materials by reducing demand for the now scarcer items (through higher price) and stimulating their production (again, through higher price), possibly through application of improved technology.

E. "TECHNOLOGY AND ESTIMATING PRODUCT DURABILITY"
BY JOSEPH JOHN, IRT CORPORATION

1. Introduction

Any attempt to estimate durability of a product has to take into account the statistical nature of failure occurrence. In most cases, there exists a certain probability distribution that describes the failure rate for a collection of identical products. Such distributions cover the average behavior of the product, but provide little assistance in exactly predicting the durability of a specific item within this collection.

This may be illustrated by analyzing a hypothetical product with some mean life, say 10,000 hours. In order to keep the illustration simple, the distribution of failure is assumed to be normal. In this case, the failure rate is distributed symmetrically about the mean life of 10,000 hours. In actual practice, however, products seldom follow such a symmetric pattern.

In Figure III-9 is plotted the probability for failure each hour as a function of the hours in operation. In this figure are shown a narrow distribution (continuous line) described by a characteristic width (σ) of 1,000 hours and a broad distribution (dotted line) with a width of 3,000 hours. Both have a mean life of 10,000 hours. The broader distribution could be attributed to a poor manufacturing process, for example. Although

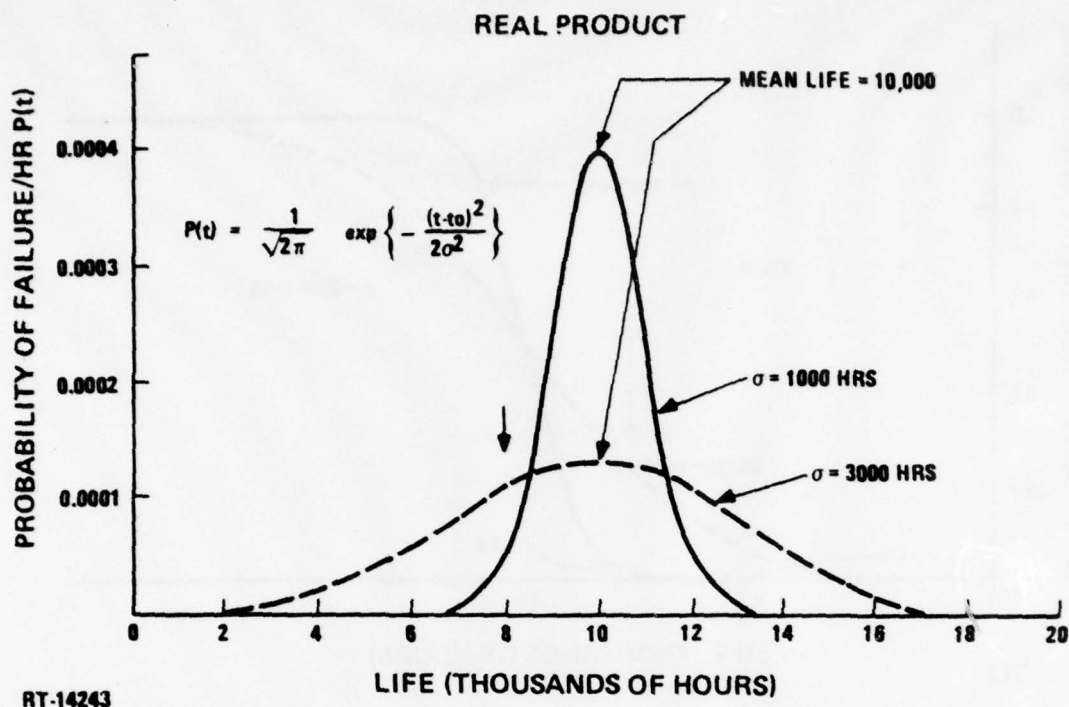


Figure III-9. Probability of failure per hour of operation as a function of service for two arbitrary cases. Each have mean life of 10,000 hours. One product is characterized by a narrow distribution ($\sigma = 1,000$ hours) while the other has a broad distribution ($\sigma = 3,000$ hours).

both distributions provide a mean life of 10,000 hours per product, the useful life obtained from the product differ significantly when high reliability is required of the product.

This dramatic difference in reliability for the two cases is graphically demonstrated in Figure III-10. Here the cumulative probability for failure is plotted as a function of the number of hours in service for the two distributions discussed above. In the case of the broad distribution, two percent failure can be expected by 4,000 hours in operation, whereas it takes nearly 8,000 hours to reach the same cumulative probability in the case of the narrow distribution. Hence, for 98% reliability, the useful life of the product belonging to the broad distribution is roughly half of that expected from the narrow group.

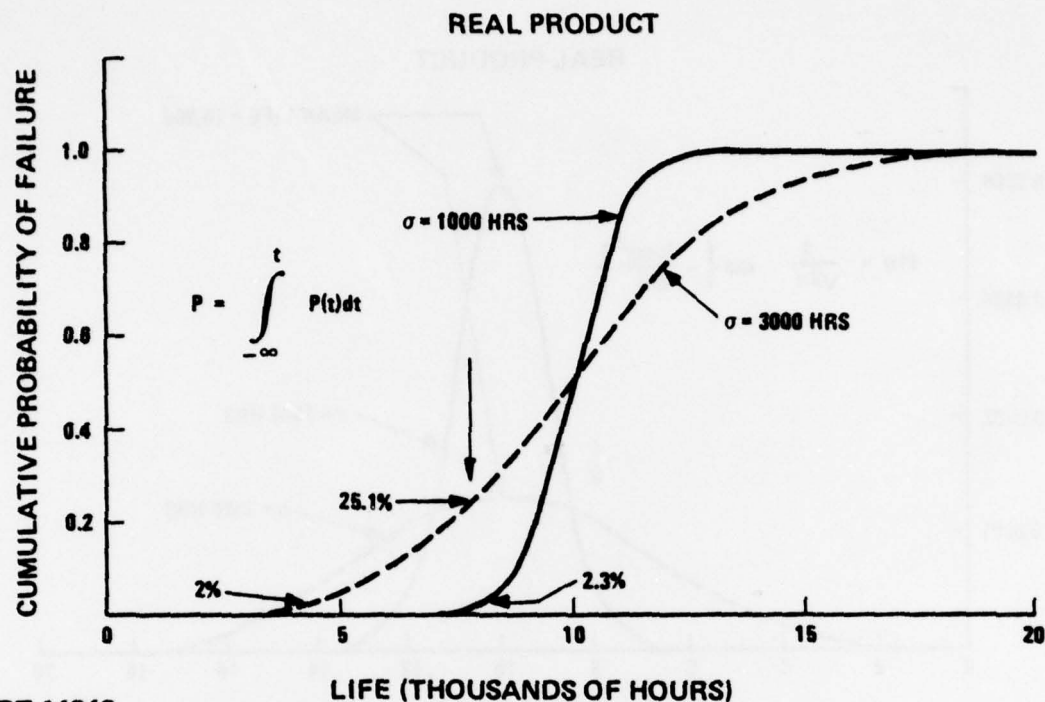


Figure III-10. Cumulative probability of failure, for the two cases shown in Figure III-9, plotted as a function of hours in service.

The effect of replacing components on schedules based only on failure probabilities is shown in Table III-6. Here the useful life and the number of parts of each group required for 100,000 hours service are tabulated as a function of cumulative failure probabilities that can be permitted. In highly reliable systems (like aircraft or nuclear reactors) the useful life is strongly dependent on the failure distribution.

The above discussion is an extremely simplified description that serves to illustrate the cost penalty that could be involved in scheduled component replacement. The parts cost component of this penalty is significant when only small failure probability could be tolerated and becomes less important as the system is allowed to become less reliable. Hence, when low failure rates are required, significant savings can be realized by CONDITION MONITORING, where a part is repaired or replaced depending on its current condition, instead of PROGRESSIVE REWORK, where a part is repaired or replaced on predetermined schedules.

TABLE III-6. USEFUL LIFE DEPENDENCE ON RELIABILITY REQUIREMENT

Cumulative Probability of Failure (%)	Useful Life, (Hrs.) (Mean Life = 10,000 Hrs.)			No. Required for 100,000 Hrs.		
	$\sigma = 1000$ Hrs.	$\sigma = 3000$ Hrs.	Diff.	$\sigma = 1000$ Hrs.	$\sigma = 3000$ Hrs.	Diff.
1	7,670	3,000	4670	13.0	33.3	20.3
2	7,945	3,250	4695	12.6	26.0	13.4
3	8,120	4,350	3760	12.3	22.9	10.6
5	8,355	5,065	3290	12.0	19.7	7.7
10	8,720	6,160	2560	11.5	16.2	4.7
20	9,155	7,420	1675	10.9	13.4	2.5
30	9,475	8,425	1050	10.6	11.9	1.3
40	9,750	9,235	515	10.3	10.8	0.5
50	10,000	10,000	0	10.0	10.0	0

2. Condition Monitoring

Hence to correctly estimate product life, it is necessary to:

- a) Precisely define failure probability distribution for the product class;
- b) Accurately determine current condition of the individual product; and,
- c) Based on these, predict failure mode.

These could be combined into an evaluation system as suggested by Bond (see ref.) and illustrated in Figure III-11 and III-12. Figure III-11 shows the organization of testing and material and information flow in most industries. A more complete evaluation system is shown in Figure III-12 where the design, testing and operational data are combined with fracture mechanics to forecast component behavior, and the results are then used to modify designs, operation or testing methods.

A major element in this evaluation process, of course, is condition monitoring. The traditional means of condition monitoring is visual inspection following component disassembly. The disassembly and reassembly operations are not only time consuming, and therefore expensive, but such operations can adversely affect product life. What is required to eliminate or reduce disassembly is Nondestructive Inspection.

3. Nondestructive Inspection Techniques

Nondestructive inspection techniques have been developed and used over the years for testing components. In addition to visual inspection, some of the more conventional techniques used are:

- a. Dye penetrant,
- b. Magnetic particle,
- c. Ultrasonic,
- d. Eddy current, and
- e. X-radiography.

With greater emphasis on product reliability, durability and material conservation, maintenance inspection has gained considerable importance. In support of this, a number of advanced nondestructive inspection techniques are evolving. These include:

- a. Neutron radiography,
- b. Laser holography,

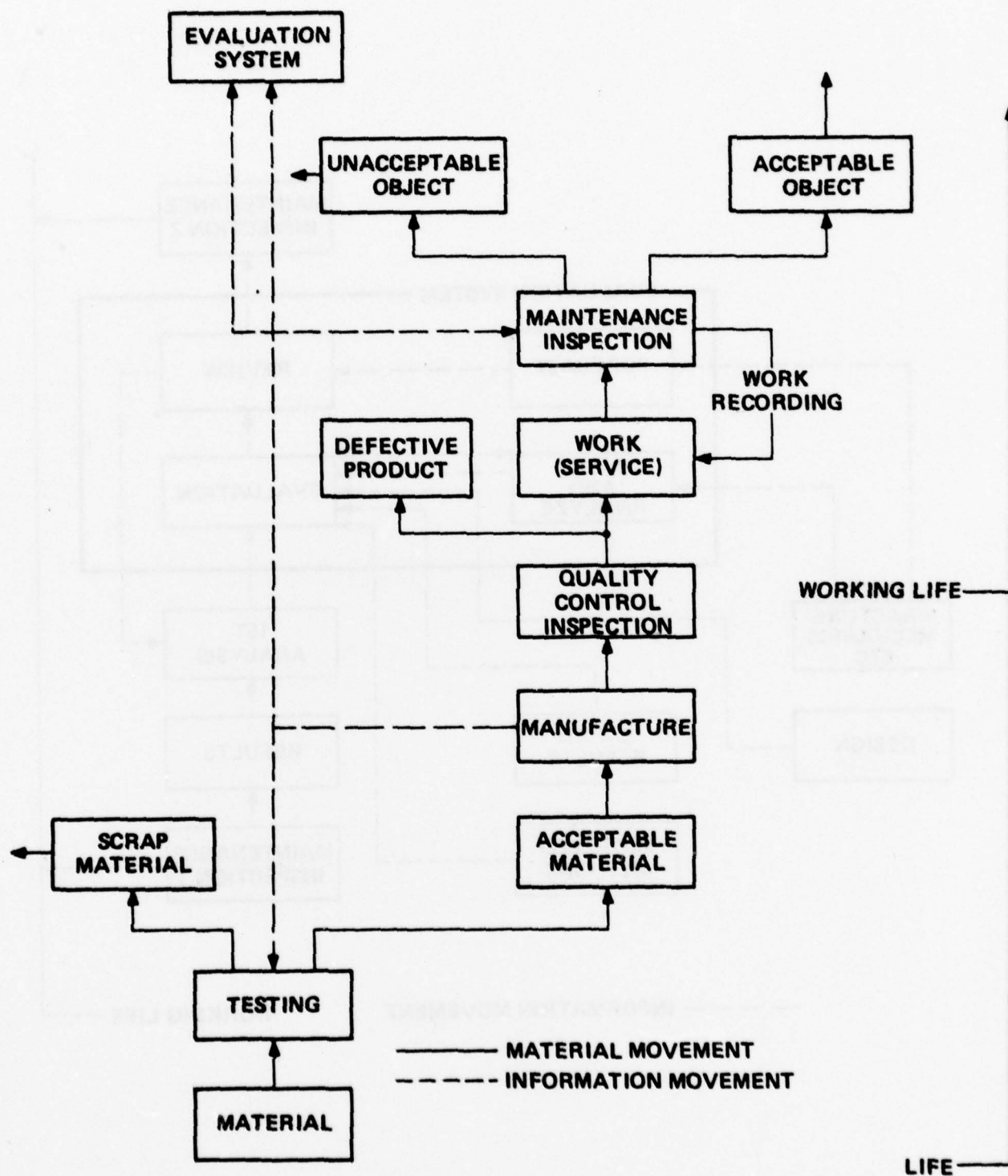


Figure III-11. Conventional Organization of Testing and Evaluation

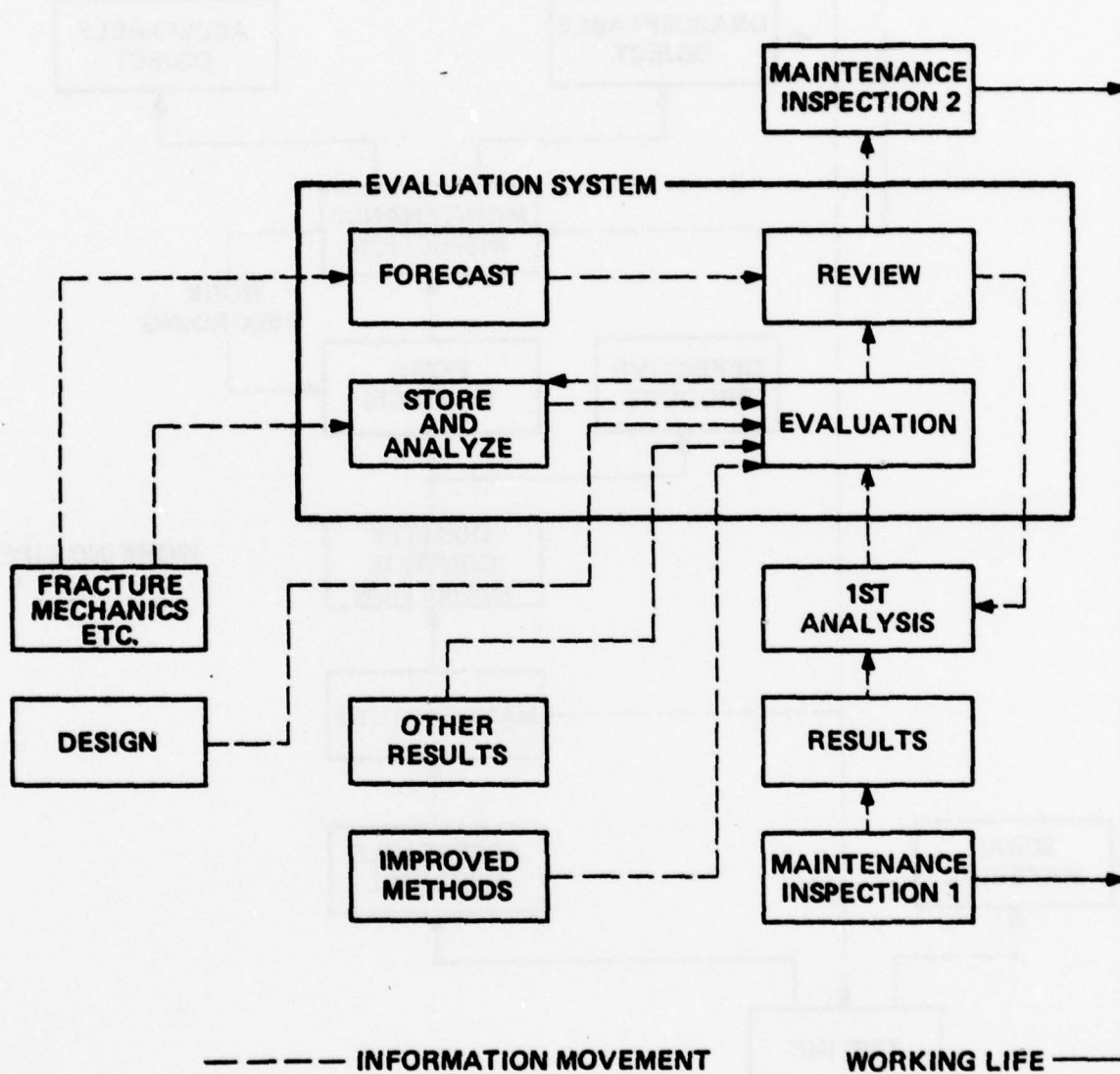


Figure III-12. Improved Organization of Testing and Evaluation

- c. Acoustic emission,
- d. Acoustic holography,
- e. Infra-red and microwave,
- f. Magnetic resonance,
- g. Mossbauer effect, and
- h. Exo-electron emission.

In addition to developing new techniques, greater emphasis is being placed on quantitative inspection to provide the necessary input to evaluation schemes.

4. Recommendation

It is recommended that any program to improve product durability must include a parallel emphasis on rapid and nondestructive inspection and evaluation techniques for the benefit of both the manufacturer and the end user. In addition, it is recommended that

- A national data bank be established for all information on materials, techniques and equipment as they apply to wear and corrosion.
- A mechanism be established for effective dissemination of this data.

Overall, it is proposed that a well-focused national research and development effort be conducted to provide improved nondestructive evaluation techniques for detecting and monitoring corrosion and wear, for developing better corrosion and wear resistant materials and improved dissemination of available information.

5. References

A. R. Bond, "Mathematical Considerations of Good Inspections", Paper presented at Management Discussions on "NDT as a Management Tool" London, 1972 (Private Communication).

- F. "ECONOMIC AND FINANCIAL CONSIDERATIONS IN THE DECISION TO REPLACE OR RETIRE EQUIPMENT"
BY PAUL LERMAN, ASSOCIATE PROFESSOR, FAIRLEIGH DICKINSON UNIVERSITY

1. Introduction

The subject of prolonging the life of capital equipment cannot be approached solely from the technological viewpoint but must be viewed also on the basis of financial

merits. For it is the financial decision-maker who ultimately decides on the replacement or retirement of equipment. Thus it is imperative to consider the subject under discussion at this meeting, improved durability through wear control, from its financial implications as well as its technological implications.

In order to do this, it is necessary to have some understanding of how financial decisions are analyzed and by necessity, this will involve a brief discussion of accounting practices as well as taxation policies. It is the purpose of this particular discussion to investigate the financial decision making process as it relates to the replacement and retirement of capital equipment.

2. A Conceptual Framework for Replacement and Retirement Decisions

Before discussing the mechanics of the financial analysis process, it is worthwhile to pause for a moment and discuss the costs associated with capital equipment as it ages. We are all aware that as machinery ages operating costs tend to increase due to requirements for increased maintenance, increased downtime, and reduced operating rates. In addition there are costs which may not be quite as obvious. These are costs that must be related to improved equipment that may be currently available for replacement. For example it may be assumed that the operating costs of the new equipment would be less than the cost of the existing equipment and, therefore, this cost must be considered. In addition there may be differences in the quality of the output between the two machines which must be considered.

Another major cost associated with capital equipment is the capital recovery cost associated with the investment itself. These costs decrease (on an annualized basis) as the equipment is utilized for an increasing number of years.

It is not only operating costs or capital recovery costs by themselves that are of interest, but rather it is the total cost of the equipment (operating costs + capital recovery costs) that is of concern. This has been shown graphically (1) as follows in Figure III-13.

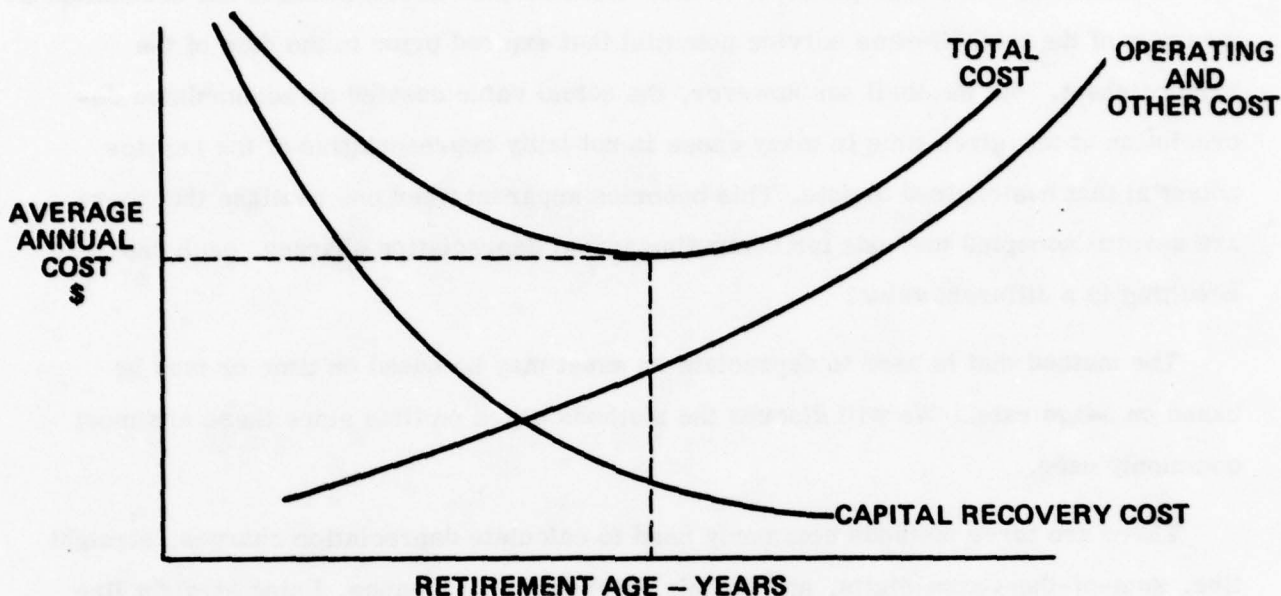


Figure III-13. Average Annual Cost of Capital Equipment

It can be seen from Figure III-13 that a tradeoff of the two categories of cost result in a total cost curve which has a minimum point at the optimum retirement age.

3. Accounting for Capital Equipment

The previous discussion should provide us with insight as to those costs which are relevant to the replacement or retirement decision, but it does not tell us how to operationally arrive at the decision. In order to understand the mechanics of the appropriate financial analysis, it is necessary to briefly discuss the method of accounting for capital equipment.

When capital equipment is acquired (that is equipment with a life in excess of one year) the cost of this equipment ultimately finds its way to the corporate balance sheet in an account referred to as plant and equipment. As the equipment ages it is depreciated and the amount of this depreciation is credited to an account referred to as accumulated

depreciation. The question arises as to just how the accountant defines depreciation. One definition that has been given (3) is that "Accumulated depreciation is the accountant's measure of the total lifetime service potential that expired prior to the date of the balance sheet." As we shall see however, the actual value carried as accumulated depreciation at any given time in many cases is not truly representative of the service potential that has expired to date. This becomes apparent when one realizes that there are several accepted methods for computing annual depreciation charges, each one resulting in a different value.

The method that is used to depreciate an asset may be based on time or may be based on usage rates. We will discuss the methods based on time since these are most commonly used.

There are three methods commonly used to calculate depreciation charges, straight line, sum-of-the-years-digits, and (double rate) declining balance. Using straight line depreciation, the charge is the same during every year of the life of the asset whereas with the latter two, the so-called accelerated depreciation methods, the depreciation charges are larger for the early years of life than for the later years. The mechanics of these computations may be found in any accounting text, for example (3). It is important however, that we review the results of each of these methods when applied to the same asset. These results are given in Table III-7. Note that each of these methods result in the same amount of accumulated depreciation at the end of the life of the asset. What is different is the timing of the charges, the effect of which will become quite obvious as we analyze the financial decision.

Since these time patterns of depreciation are quite likely not to be representative of the true service potential that has expired, the question arises as to why we are interested in these methods at all and how do they affect the decision to replace equipment. The fact of the matter is that the depreciation method plays a large part in this decision through the effect of corporate income taxes. Depreciation is an allowable expense in the computation of taxable income, and tax considerations play a substantial role in all financial decisions.

TABLE III-7. COMPARISON OF DEPRECIATION METHODS

EXAMPLE: Original asset cost = \$36,000

Salvage value = \$1,500

Life = 12 years

Year	Sum-of-the Years' Digits		Double-rate Declining-Balance		Straight-Line	
	Beginning Book Value	Annual Charge	Beginning Book Value	Annual Charge	Beginning Book Value	Annual Charge
1	\$36,000	\$ 5,308	\$36,000	\$ 6,000	\$36,000	\$ 2,875
2	30,692	4,865	30,000	5,000	33,125	2,875
3	25,827	4,423	25,000	4,167	30,250	2,875
4	21,404	3,981	20,833	3,472	27,375	2,875
5	17,423	3,538	17,361	2,894	24,500	2,875
6	13,885	3,096	14,467	2,411	21,625	2,875
7	10,789	2,654	12,056	2,009	18,750	2,875
8	8,135	2,211	10,047	1,709	15,875	2,875
9	5,924	1,769	8,338	1,709	13,000	2,875
10	4,155	1,327	6,629	1,709	10,125	2,875
11	2,828	885	4,920	1,709	7,250	2,875
12	1,943	443	3,211	1,709	4,375	2,875
13	1,500	-	1,502	-	1,500	-
Total		<u>\$34,499</u>		<u>\$34,498</u>		<u>\$34,500</u>

Note: For double declining balance the depreciation rate is twice the reciprocal of the asset's expected life, with no explicit recognition of end-of-life salvage. The depreciation charge stabilizes at \$1,709 in the eighth year. This is necessary if the depreciation charges are to reduce the machine's book value to \$1,500 at the end of 12 years. The practice is to switch to straight-line depreciation in the year that the declining balance charge falls below the average remaining depreciable amount. This took place in the eighth year.

4. Corporate Income Taxes

Without discussing the very complicated Federal Income Tax laws in any great detail it will serve our purpose to note that corporate income taxes are computed as follows (taxable income year 1975):

Normal tax: 20% on first \$25,000 of taxable income, plus
22% on taxable income over \$25,000
Surtax: 26% in taxable income over \$50,000.

Thus in effect the stated tax rate for corporations of any substantial size at all is 48%. Historically this rate has been approximately 50%. Note that this rate is applied to taxable income which is arrived at through subtraction of certain expenses, including depreciation, and other allowable deductions from gross income. It is a simple matter to compute that each additional dollar of depreciation expense (which in itself is a non-cash charge) results in a saving of \$0.48 in tax payments.

One other feature of the current tax law that should be mentioned is the investment tax credit. The investment tax credit, which the Tax Reduction Act of 1975 raised to 10% for a limited period permits a credit based on asset cost against tax liability when certain qualified business property is placed in service (a credit is subtracted directly from tax liability resulting in a \$1.00 tax saving for each \$1.00 of credit). The amount of the credit is computed, with some exceptions by taking 10% of the cost of the asset if the asset has a life of at least seven years. If useful life is at least five years but less than seven years, two-thirds of the cost qualifies; if at least three years but less than five years of life, one-third of the investment qualifies. No credit is allowed for property with a useful life of less than three years.

The rationale for the institution of this credit is the stimulation of investment in a recessionary economy. The effect of this law from a materials conservation viewpoint is less clear. The law encourages "premature" equipment replacement by reducing the cost of the asset but this may result in replacements which are more efficient having the effect of reducing energy consumption as well as the consumption of other scarce resources.

5. Example of the Financial Analysis of a Replacement Decision

An excellent example of an equipment replacement analysis is given by Van Horne (5) which will be used to illustrate the methodology.

Consideration is given to the purchase of a turret lathe to replace an old lathe. The old machine has a depreciated value of \$2000 and it can be sold for this amount. The estimated remaining life of the old lathe is five years.

The new machine has a purchase price of \$18,500 and will require installation at a cost of \$1,500. This machine is expected to cut labor and maintenance costs and effect cash savings totalling \$7600 annually before taxes for the next five years after which there will be no saving, and it is not expected to have any salvage value. We will assume a tax rate of 50% and straight line depreciation.

The accounting analysis of the annual savings follows:

	Book Acct.	Cash Flow Acct.
Annual Cash Saving	\$7,600	\$7,600
Depreciation on new machine	4,000	
less depreciation on old machine	400	
Annual Depreciation Charge	\$3,600	
Annual Income before Taxes	4,000	
Income tax (50%)	2,000	2,000
Additional Income after Taxes	<u>\$2,000</u>	<u>\$5,600</u>
Annual Net Cash Flow		

Which of these "bottom line" figures is the correct one to use to describe the real benefits associated with purchasing the new lathe? Reflection on this question will lead us to the conclusion that it is the cash flow account that truly measures the incremental effect of replacing the lathe. More simply stated it is the cash flow account which measures the actual amount of money that has flowed into (or out of) my pocket because of the investment. The only use that is made of the book account is the computation of income tax liability due to the investment.

Having identified the benefit associated with the replacement, the next step is to evaluate the investment in light of these benefits. There are several possible methods of evaluation, but there is one in common use today which is the most logical and which leads to unambiguous results. This method is referred to as the Net Present Value (NPV) Method. Simply stated this method finds the "present value" of the future stream of cash flows. The basic equation used in this regard is a simple rearrangement of the formula used in the computation of compound interest. Letting

C_n = cash flow at the end of year n

P = present value of C_n

k = discount rate

we can write the present value of a single cash flow as:

$$P = \frac{C_n}{(1+k)^n}$$

Thus for an investment associated with n periods of life the NPV expression may be written as:

$$NPV = -C_0 + \frac{C_1}{(1+k)} + \frac{C_2}{(1+k)^2} + \dots + \frac{C_n}{(1+k)^n}$$

The value of discount rate, k , that is used is usually the minimum return on investment required by the decision maker. C_0 is the initial cash outlay (net).

For the example at hand assume that the required return is 10%. Therefore we may write:

$$\begin{aligned} NPV &= -18,000 + \frac{5,600}{(1+.1)} + \frac{5,600}{(1+.1)^2} + \dots + \frac{5,600}{(1+.1)^5} \\ &= -18,000 + 5,600 \sum_{t=1}^5 \frac{1}{(1+.1)^t} = -18,000 + 5,600 (6.1446) \\ &= -18,000 + 34,409.76 = \$16,409.76 \end{aligned}$$

The numerical value that is the result of the NPV computation is compared to zero, since if the result of the computation were to be zero this investment would be earning precisely 10%. Since the result of our computation was greater than zero, the investment is earning in excess of 10%. Likewise if the result had been a negative value for NPV the investment would earn less than the required 10%.

More important than the problem at hand, the basic NPV equation for evaluating an investment provides us with some important observations regarding what the characteristics of a "good" investment should be. First of all, we note that as we add more terms to this equation (representing additional years of life of the investment) assuming cash flows remain constant, the effect of each succeeding term on NPV is smaller than that of the term before it due to the increasing nature of the denominator. This observation provides some insight into the value of accelerated depreciation methods since the tax benefits of these methods accrue in the early years. We also should note that this time effect becomes even more pronounced as the discount rate is increased. It has not been uncommon in recent years for corporations to use a discount rate of 20% in analyzing capital investments. This is indicative of a desire to reap the benefits of a capital investment as soon as possible.

These observations have important implications for the subject at hand, that of increased equipment durability. If the only improvement in equipment is to extend its life at an increased initial cost, it is questionable as to whether this increased initial cost can be justified financially when viewed from the standpoint of NPV. However, if in the process of extending life the equipment were made more efficient in terms of energy requirements, reduced maintenance, reduced downtime etc., resulting in larger positive cash flows throughout the equipment life it may be possible to justify the increased initial cost. One other possible method of altering the cash flow pattern for equipment with extended life may be found in an appropriate tax policy.

6. Optimum Service Life Decisions

There are several models that have been developed to determine optimal service life of capital equipment. Most of these models are based on the NPV expression that has already been discussed. In particular two of these models, "The Pure Retirement Model" and the "Constant Chain Replacement Model" are based on the NPV equation with the intent being to find the retirement or replacement date so that the value of NPV is maximized. A description of these models may be found in Bierman and Smidt (2) and Mao (4).

7. Summary

It has been the intent of this paper to discuss those aspects of the financial decision making process which have an effect on the actual service life of capital equipment. As individuals who have come together at this conference to investigate the advancement of technology resulting in material conservation we must recognize that any solutions toward this end must be financially viable or corporate decision makers will not implement these solutions. Hopefully, this paper has provided some insight into this particular decision making process.

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CHAPTER IV

TECHNICAL PAPERS PRESENTED AT THE AFTERNOON SESSION

- A. "FOUR E's OF POWDER COATING: ECOLOGY, ECONOMY, EFFICIENCY, EXCELLENCE"
BY HANI T. AZZAM, INTERRAD CORPORATION

Known as the four E's of powder coating, these factors have had a great deal to do with the growth and acceptance of powder coating in the U.S. market. When a fifth E - Energy is added, the significance of powder coating as a finishing method for industrial coating becomes obvious.

1. Ecology -- Energy

Actually the pollution issue popularized the concept of powder coating in the late 60's. Los Angeles' Rule 66, which placed a limit on the amount of solvents that could be emitted into the atmosphere, forced the industrialist to take a good hard look at the substances within his finishing operation.

A study made by Hardy & Seitz of Sherwin Williams documents the magnitude of the solvent problem in the coating industry. Considering four alternative coating methods including solvent enamel, high solids, water borne and powder, the solvent content ranged from a high of 65% with solvent enamel, to 20% with high solids, 14% with water borne and 1% with powder.

Solvent clearly became the safety issue in the analysis of the pollutants emitted by the coating systems of the U.S. The DuPont Company took a look at the solvents emitted in terms of annual waste. In an annual application of 177 tons of solids at 1.5 mils, their study showed a dramatic differential with 168 tons of volatile solvent waste for the solvent base system in contrast to just 2 tons for the powder system, measured over the same one year period.

Taken in such large volume, the problem of waste placement for the coating system became another critical issue for the industrial finisher.

Added to this waste elimination problem, the necessity of replacing the air displaced by the solvent in the booth (application area) itself gave the finisher an additional air requirement, determined by the size and volume of his particular system. He had to heat and replace that air in order to maintain a safe operating system. In powder, this was not the case. And with the problems of reduced energy availability at a higher cost, powder looked even better.

Toro, a lawn equipment manufacturer in Windom, Minn. with a 12 million sq. ft. annual production, recently chose a powder coating system to replace their existing solvent line. They did so as a part of their company wide energy savings program. Their computations projected an annual energy savings of 4-1/2 Billion BTU's with powder or 10% of their current energy expenditures. This savings is a direct result of the reduced air make up and exhaust requirements that go with the powder system. The reduction in exhaust and energy requirements in turn mean lower natural gas requirements in the critical peak demand periods of Midwestern winters. For example, last winter Toro had to go on propane gas for 60 days at a cost of \$180,000. With their new lower energy requirements, they projected savings of \$30,000 for the coming winter.

In addition, the powder system will not require the continuing sludge removal expenditures, including the cost of carting semi-loads of sludge in 55 gallon barrels to incineration plants 150 miles away at an annual savings of \$8,750. Add to this, the savings on rejects with high cost of chemicals needed for stripping and cleaning which amount to \$25,000 annually or 50% of current expenditures, and the economics of powder becomes very clear.

2. Efficiency--Economy

Powder as a coating agent offers the benefit of substantial material savings. Unlike the wet systems that lose the material not directly applied to the product, the powder systems can reclaim the powder not applied in the first pass, recycle and reuse it for coating the product.

Two case studies document powder's particular efficiency as well as its economizing features.

Singer, Anderson, South Carolina, for example, chose electrostatic powder coating to replace their solvent wet system. In the transition, they made extensive studies of the coating process. In their final switch to powder, they were able to cut the finishing process from 27 steps with the liquid application to 9 steps with powder.

Elimination of the primer coat, as well as the need for sanding and masking accounted for some of the savings. As an added benefit, the powder finish applied in one coat was so tough that the product could be machined after coating, saving additional time. Not only did the sewing machine finish meet Singer's specifications, it did so at a savings of \$1.00 per machine.

Sylvania, Reidsville, North Carolina, found that a switch to powder meant an increase in the reflectance (a requirement for their fluorescent lighting fixtures). They upped it to 90% with the powder finish, in contrast to 87% for the baked enamel fixture and 83-86% for the porcelain fixture.

In a series of tests including pencil hardness, salt spray resistance, humidity resistance, gloss and impact, powder outscored both the baked enamel and porcelain applications.

But the economic considerations are even more impressive (see Ref.) given the choice of either expanding the existing liquid system or installation of an entirely new powder finishing system, Sylvania found that powder met their increased production requirements with the following operating cost savings as documented. (See Table IV-1).

3. Improvements in Application Equipment

During the past year, powder application equipment has gone through a revolution of sorts. A new continuous filter belt located within the actual coating booth has replaced the cumbersome baghouse units for reclaiming powder. The new belt, which works in conjunction with a small cyclone unit also increases reclaim efficiency to 100%, meaning total material recovery. Naturally, this new simpler design has accelerated interest in powder application since the process can now be completed more efficiently in a smaller area with fewer components. This accelerated interest has

TABLE IV-1. OPERATING COST SAVINGS POWDER VS. WET SYSTEMS*

	1974	1975	1976
Capital Costs	None	\$ 30,000	None
Labor	\$23,900	39,140	\$146,000
Royalties	13,656	16,387	20,484
Clean-Up	7,572	9,858	11,358
Sludge Disposal	1,115	1,400	1,673
Maintenance	6,000	6,350	9,000
Utilities			
Gas	3,085	3,485	6,170
Water	212	348	424
Electric	1,238	1,575	2,476
TOTAL SAVINGS	\$56,778	\$108,513	\$197,585

*Key to Table as noted in paper by H. Homer

"Labor savings in 76, reflects elimination of need for second shift. Savings on electrical costs were computed by Duke Power Co."

"Increased costs during 1975 and 1976 reflect the addition of 3rd. Handspray booth and second shift."

"Savings in gas consumption reflects lower ventilation requirements."

"As exhaust air from powder system can be filtered and returned to the plant, plant air make up can be reduced by 90,700 CFM. In addition, oven exhaust can be reduced as much as 40% once system is fully converted to powder savings in natural gas, costs shown are based on 1973 price of 40 cents per million cubic feet."

motivated large volume customers in appliance and lighting fixtures to go with the fully automated capacity of the new belt system.

4. The Market

Powder coating shows signs of growing strength. With a penetration of 7.5% of the industrial finishing market, the industries that have been with powder since the beginning: automotive accessories, bicycles, electrical equipment, farm and garden

equipment, fire extinguishers, glass bottles, lighting fixtures, metal furniture, appliance, including air conditioners, freezers, refrigerators, sewing machines, washing machines, are continuing to purchase the latest in powder technology.

With the continued influence of the original 4 E's as well as energy, prognosis for the future in powder is positive, with a continuation of today's high growth rate definitely in the marketing program.

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B. "AUTOMOBILE DURABILITY" BY DAVID J. BARRETT, FORD MOTOR COMPANY

Good afternoon, ladies and gentlemen. I have been asked by our hosts to present a viewpoint on automobile durability as it relates to the conservation of several metals which are used extensively in Ford Motor Company passenger cars. Although the

primary concern of this workshop is the wear of these materials, it is my intent to discuss the more general aspects of automobile durability.

Today's automobile is probably the most complex consumer durable product ever mass-produced. Typically it contains about 15,000 components, many of which are moving parts. It is designed for operation under a wide range of operating environments, including ambient temperatures ranging from -20° to +120° F; air and road conditions ranging from clean and dry to salt saturated and wet; road surfaces ranging from those of the interstate highway system to the rutted, bumpy back roads in remote rural areas, and elevations ranging from below sea level to upwards of 14,000 feet.

The modern automobile is designed to provide customer safety, comfort and convenience under all of these conditions even in the least expensive "Base" vehicles -- and to optimize comfort and convenience through incorporation of such features as climate control systems, automatic transmissions, power steering and brakes and sophisticated electronic entertainment systems. And, due to the economics of large-scale manufacture, these "plus" features are made available at prices that a large proportion of auto consumers can afford.

Moreover, government standards on safety, emissions and noise have caused a substantial additional increase in the complexity of our products.

I'm sure you've all heard the accusation that automobiles are designed for planned obsolescence. It is typified by the joke about the guy who makes the last payment on his car and walks out to find it collapsed in his driveway.

In contrast to that joke, let me cite an unsolicited testimonial that came to my attention the other day from the owner of a 1969-Ford intermediate-sized station wagon. He wrote that some years ago, when the station wagon already had 100,000 miles on it, he wanted to buy a new boat. He debated whether to purchase a new wagon and defer the boat purchase or gamble on the wagon lasting and buy the boat, since he couldn't meet the payments on both a new wagon and the boat. He wrote to say he gambled on the wagon, and had completely paid off the boat. Furthermore, with boat towing added to its pedigree, the wagon is still going strong at 176,000 miles.

I wish I could tell you that 176,000-mile station wagon is typical or better yet, below average. But I can't, nor can anyone else. Unlike producers of other consumer goods, we simply cannot tell you what the product life, or durability, of a given vehicle will be -- in terms of miles or years. The fundamental reason we cannot is the incredibly random use to which our vehicles are subjected.

And because of this randomness, we do not know how to design the complete vehicle to any absolute limit of miles or years.

We do, however, have the ability to identify specific parts or components with high repair rates, and we have a strong incentive to improve them.

Our most sophisticated customers are large fleet purchasers who generally have the capability of evaluating product durability themselves and to whom the resale value of the car when it is only a year or two old is a critical part of the purchase decision. This is especially true of daily rental firms which, in many instances, replace cars twice a year. The inherent durability of a car becomes especially important to individual new-car purchasers as a trade-in factor when the particular model is several years old. Since the average new-car purchaser retains his vehicle 4 to 5 years, the value of his old car tends to influence his decision about the kind of car he will buy to replace it. If durability is good compared to competition (all other things being equal), the trade-in value of his car will be relatively high and he is likely to remain "loyal" and purchase his new car from the same manufacturer. Accordingly, the manufacturer has very compelling reasons for assuring that his car's durability and repair record is at least comparable to that of his competition.

The consumer is interested, of course, in reducing his total ownership cost. This means achieving the best balance among initial purchase price, operating cost including both scheduled and unscheduled maintenance, and trade-in value. The relative importance of these factors varies greatly depending on the income of the purchaser, his ability and interest in maintaining the vehicle himself, the amount and type of use of the vehicle, and the length of time he plans to retain the car before trading it in. The balance among these factors is complex, but the aggregate decisions made by purchasers ranging from

sophisticated fleet-buyers to individual purchasers of all kinds constitute the competitive pressures the manufacturer must consider in improving product durability.

We normally think of durability as the potential useful life of a product as distinct from its expected or actual useful life. The actual useful life of today's automobiles is dependent on many factors. These factors include the durability that is designed into the automobile, the care which the owner exercises in operating and maintaining it, features and functions of the vehicle compared to those available on or inherent in a more recent model, and finally, the economics of performing maintenance vs. scrapping the car and buying a replacement, whether new or used.

A car's life ends when it is "retired." This could happen the moment it drives out of the new car show room and is hit head-on by a truck. The insurance claims adjuster concludes it would cost more to repair the damage than the car is worth, so it is "retired" with virtually zero miles and zero time. At the other end of the spectrum -- and importantly there is no body of research on specifically why it happens -- a car is "retired" because the last operator decides it isn't worth keeping any longer. The market value has declined to, say, \$50 for the old car and it needs a new set of tires for \$100. The owner can buy a different or better vehicle for somewhat more money and he decides to retire the old car.

Durability improvements, as measured by controlled laboratory and proving ground tests, will continually be incorporated into our cars, but these increases in potential component life alone will not likely have any significant effect on actual vehicle life, because today's chassis and drivetrain components are already designed to have a potential life that significantly exceeds the time the vehicle is likely to be in service. Ford has very stringent material specifications, and these are continually reviewed and upgraded based on new technology and field performance. It has been reported that our specifications are only exceeded by those used in the aerospace industry. Additionally, Ford's laboratory and proving ground durability testing requirements have doubled in the last 20 years for major vehicle components, including frames, engines, front and rear suspension systems, axles and transmissions. Durability requirements for other, less critical components, have also been upgraded significantly.

Vehicle and component durability are confirmed through an elaborate series of laboratory and proving-ground tests. We have the equipment and techniques to simulate long term customer usage of a vehicle or its components in the laboratory in a matter of weeks. The durability of components is evaluated through laboratory tests and on prototype vehicles while they are under development, again at the pre-production level and, finally, production parts are analyzed for compliance with our even higher acceptance standards.

Prototype vehicles are subjected to thousands of miles of "worst-case" testing at our proving grounds; they are operated over cobblestones, square-edged potholes, and other road surfaces designed to bend, twist, stress, fatigue and wear out parts. Problems which show up are corrected, and the whole process is repeated again.

In addition, we make extensive use of fleet testing to supplement the information gained at our own facilities. Newly designed components are installed on fleet cars, (some of which accumulate in excess of 800 miles a day), to acquire actual service experience on new parts prior to their release for production. Representative production vehicles are also tested on our proving grounds to assure conformance to the same stringent requirements.

Some of the product improvements incorporated during the last twenty years include:

- Solid state ignition systems have eliminated the wear out of distributor points.
- Improved engine water pump bearings and shaft seals allow the pumps to last for the lifetime of the vehicle.
- Improved body paint formulation with acrylic enamels.
- Interior trim materials, such as carpets and seat covers, have been improved for significantly longer life.
- Introduction of disc brakes has resulted in longer lining life. (Disc - 32,000 miles vs. Drum - 25,000).
- Use of steel belted radial ply tires increased tire life to 40,000 miles vs. 18,000 miles for conventional bias ply tires.

To ensure that the production parts are manufactured and assembled with the durability and reliability designed into them, elaborate quality control and inspection

procedures are followed. The Ford Supplier Quality Control Specification is recognized as one of the most stringent in the industry.

Improvements in the life of those components designed to minimize friction have been even more dramatic. Over the years we have continually upgraded bearing materials, lubricants and lubrication techniques. When recommended lubrication intervals are observed, these components are just not expected to wear out.

These advances in durability have been accompanied by significant reductions in the need for scheduled maintenance. A comparison of selected service operations as recommended in the owner's manual for 1976 models versus 1956 models shows that the lubrication interval for suspension components has increased from 1,000 to 30,000 miles; engine oil change interval has increased from 2,000 to 5,000 miles; automatic transmission fluid replacement, formerly required every 10,000 miles, is no longer required.

These durability improvements have always been incorporated after study of the complex inter-relationships among safety, fuel consumption, purchase price, maintenance cost, comfort and a host of other factors that both consciously and otherwise, enter into the initial decision to purchase a car -- and into the even more complex decision about "which car to buy next time."

The objectives, of course, are to reduce the need for owner maintenance, to reduce the number of necessary repairs during the vehicle life, and to increase the length of time vehicles are used. We have demonstrated some Ford actions that have been taken over the last 20 years to increase vehicle life potential, improve the durability of key materials and components, and reduce the need for owner maintenance. We believe our competitors have taken similar actions.

While we know that potential life has increased as a result of these actions, we also know that actual vehicle life has remained relatively stable. R. L. Polk registration data for the composite of all makes and models show that median car life -- the age at which 50% of the vehicles of a particular model year are retired from service for the total United States -- has remained at about 10 years for 1955 through 1965 model cars.

Since only a small proportion of cars of a given year are retired during the first few years -- less than 20% after seven years -- it is not possible to calculate median life for more recent model years. The data that are available, however, indicate that median life for more recent model years (1966 - 1970) will be about the same as or slightly less than for the 1965 models -- about 10 years.

Objective data also tells us that the average age of cars increased during World War II and that, in the recent recession, fewer cars were retired. In the first case, no replacements were available and in the latter case, economics dictated that car owners delay major purchases such as new, or even higher valued used, cars.

Furthermore, we have some subjective data which suggest that cars can and do last almost indefinitely, even when replacement parts are hard to come by. Take Cuba, where reporters tell us the streets are still filled largely with 1950's-vintage American cars. Or I could read you unsolicited testimonials all afternoon about 100,000-mile or even 200,000-mile cars.

It seems clear, then, that increasing potential durability will not alone achieve the objective of longer-life products. One of the keys appears to be the way vehicle owners use and maintain their cars. As regards the influence consumer maintenance has upon vehicle life, there are several important data sources available. These data sources are measurements of the influence of mandatory periodic motor vehicle inspection programs (PMVI) upon median car life.

In Sweden, median car life was found to increase by about four years after a compulsory motor vehicle inspection program was established in 1965. Under the strict Swedish motor vehicle inspection program, vehicle life has gone from about 10 years in 1965 to 14 years in 1974, while median car life in the U.S. has remained at about 10 years.

Limited data available for two pairs of states in the U.S. tend to corroborate the Swedish experience. Pennsylvania and Virginia, which have had periodic inspection programs for many years, were compared, respectively, with Illinois and Maryland,

which do not have such programs. By comparing Pennsylvania with Illinois and Maryland with Virginia, we can evaluate car longevity in pairs of states whose size, climate, income distribution and degree of industrialization are comparable. We found median car life in the states with inspection programs, Pennsylvania and Virginia, 7 months and 20 months longer than in the respective non-inspection comparison states of Illinois and Maryland.

It is our belief that compulsory vehicle inspection programs -- even when related to safety only -- affect car life in two ways. First, and most important, the owner is required to maintain the safety-related operating components of his vehicle, e.g., brakes, lights, exhaust systems, tires, etc. This has the effect of reducing the rate at which the vehicle depreciates, and thus provides greater incentive for the owner(s) to keep the vehicle on the road longer. Second, the basic theory of periodic safety inspection is that vehicles which are better maintained are less likely to be involved in collision with other vehicles or objects. Obviously, the fewer accidents a car is involved in during its life, and/or the less severe the damage sustained in accidents, the lower the cost of repair and thus the greater the likelihood the vehicle will remain in operation.

Ford and the Motor Vehicle Manufacturers Association (MVMA) have consistently supported the PMVI programs for years because of their importance in improving vehicle safety. More recently, we have urged that PMVI programs be broadened to include inspection of noise-related components; and, especially, functional checks of emissions-control devices, to help assure that the air-quality improvements that the public is paying for are indeed accomplished. Tests that assure that vehicles are tuned to manufacturer's specification will be beneficial to the control of emissions and fuel economy. The need to conserve natural resources, and the relationship between PMVI programs and car longevity, now provide an additional compelling reason for urging the adoption of PMVI.

Despite strong support for these programs by both our industry and the Department of Transportation, 19 states still are without operative periodic vehicle inspection programs. Beyond that, those state inspection programs that do exist vary widely in implementation and enforcement standards and therefore in effectiveness.

We believe there are compelling reasons for all states to have periodic inspection programs, and that Federally developed performance guidelines should be used both to upgrade existing programs and to formulate new ones. Furthermore, we support Federal incentive grants to encourage the remaining 19 states to adopt effective vehicle inspection programs.

We recognize, of course, that periodic motor vehicle inspection is opposed by many because they fear that the cars removed from the road as a result of PMVI will be vehicles owned by people in low income brackets. The Swedish experience did show that a fairly large number of cars were "retired" during the first year of the program. This is a consequence which cannot be avoided, but it is short-lived and thereafter the cars which are purchased by people in low income brackets are in better condition and will last longer. Further, it seems obvious that no service is done people in low income brackets by permitting them to expose themselves and others to greater danger from improperly maintained vehicles.

We do not mean to suggest, however, that the problem is all the fault of the consumer. Over the years the automobile has become a much more complicated piece of machinery as automobile manufacturers have responded to a myriad of consumer demands for comfort and convenience equipment, and government requirements related to safety and emissions. As the vehicle becomes more complex, it becomes more expensive, and often much more difficult to repair. More sophisticated equipment is required both to diagnose a problem and accomplish the repair. Mechanics need more training than ever before. And it becomes much more difficult always to have the right part available at the right time.

To assist consumers in having their vehicles repaired, Ford Motor Company has undertaken programs to improve the serviceability of the products and to reduce consumer cost and inconvenience of having automobiles serviced. The Company has established specific serviceability objectives at program approval time for all forward model designs. These objectives are to reduce the amount of time to repair or replace damaged or worn-out components such as spark plugs, shock absorbers and fan belts.

In addition, in 1966 the Company started operating its own vehicle diagnostic center, to provide dealer service personnel with the newest techniques in identifying causes of automotive problems. As new advances are made in problem diagnosis and repair, dealer service-personnel are informed through service bulletins and training publications.

Many of our dealers, who of course are independent businessmen, also have encouraged their service mechanics to participate in the mechanics certification programs sponsored by the National Institute for Automotive Service Excellence. Through this self-help program, mechanics are trained to identify the cause of the trouble and to correct the problem faster which results in lower repair costs. Furthermore, dealers are attempting to reduce the inconvenience of having cars serviced. Examples of this include: providing loaners if the car has to remain in service overnight, and locating dealerships near shopping areas where other errands can be performed while the automobile is being serviced.

There is a clear national interest in conservation of finite natural resources and energy; but we believe increased potential vehicle durability would not have a major effect on actual vehicle life. It should also be pointed out that an automobile that is retired from service does not represent anywhere near total loss of the materials used to build the car. According to a recent Department of Transportation study, prior to 1973 an average of 80 to 85% of the vehicles "retired" each year were being recycled through existing scrap-recovery channels. More recently, in 1973 and 1974, it has been estimated that more vehicles were recycled than the number "retired" from service. This resulted in a reduction in the national inventory of junk vehicles but for this progress to continue, we believe more state-organized junk vehicle recovery programs must be approved. For many years, our industry has advocated that such programs be financed by a modest increase in the annual fee for vehicle licensing registration, or title transfer. A number of states, including Maryland, have adopted vehicle disposal programs in the last few years, and other states are considering similar action. In addition to the high percentage of vehicles recycled, the recovery rate per vehicle is extremely high. On average, 90-95% of the materials in junk vehicles are recoverable. In fact, in some recycling operations, once the gas tank and tires have been removed,

almost 100% of the material resources contained in obsolete vehicles are reclaimed. There is, of course, a limited amount of energy consumed in converting the reclaimed materials into new products. This is not intended to suggest that there is no problem -- but only to help place the problem and its individual elements in their proper perspective.

Let me briefly summarize what I have tried to document about durability in the auto industry.

First, every vehicle manufacturer has a clear and demonstrable competitive interest in improving the durability of its products.

Second, Ford Motor Company has continuously incorporated changes to improve the durability of its products as well as to reduce the need for customer maintenance -- and our competitors appear to have taken similar actions.

Third, vehicle and component durability improvements over the last decade or so do not appear to have had a major effect on actual vehicle life.

Fourth, there is clear evidence that mandatory periodic motor vehicle inspection programs produce measurable increases in actual automobile life.

Fifth, at the end of their useful life, most vehicles entering the recycling system and virtually all of the vehicle material content is reclaimed.

C. "ECONOMIC IMPACT OF TRIBOLOGY (UK EXPERIENCE)"

BY D. SCOTT, NATIONAL ENGINEERING LABORATORY/WEAR PUBLICATIONS

1. Introduction

In the present and foreseeable future economic situation in the UK, material and energy conservation is becoming increasingly important. As wear is a principal cause of material wastage, and its associated friction a cause of energy dissipation, any reduction of wear can effect considerable savings. To illustrate the costs involved it has been reported¹ that a simple bearing failure in a fully integrated steel mill can lead to a total shut-down which at full output rate may cost £150- £300 per minute. A similar bearing failure on a modern generator set could involve the Central Electricity Generating Board in a loss of £1- £20 per minute till the set was again operational.

The British Government's concern about wear was such that a Working Group studied the position of education and research in lubrication and gave an opinion of the needs of British industry in the field. The Lubrication Report² renamed the subject 'Tribology' - "The science and technology of interacting surfaces in relative motion and the practices related thereto". The principal findings were that industry suffers considerable losses resulting from inadequate appreciation of tribology, and that the basic cause of this state of affairs lies in industry's lack of awareness of the subject. It was estimated that an amount probably exceeding £515 million per annum can be saved by improvements in education and research in tribology. With inflation, this figure has probably risen to £1000 million today. Such improvements are significant not only in cost saving but for material and energy conservation. They are crucial to technological progress and have doubly significant implications for the economic well-being of the nation and the reputation of British engineering products. Featuring prominently as the major cause of plant breakdowns and failures was wear.

It is now a decade since the word Tribology entered the English language and therefore a convenient time to assess its influence and economic impact in the UK.

2. Advisory Services

The National Centre of Tribology and Industrial Units of Tribology were set up at Leeds and Swansea to provide expert advice to industry on the utilization of existing and new knowledge in Tribology which was not being effectively applied. Tribology advisory services, in addition, continued to be provided by NEL. Each has provided a comprehensive service to meet the wide and diverse range of problems presented by industry³. The three new centres were provided with Government deficiency grants but are now viable establishments operating as contact research organizations selling their services at commercial rates.

3. Education and Training

Over 30 universities, polytechnics and technical colleges have incorporated courses on various aspects of tribology into their syllabuses. A basic tribology module⁴ for undergraduate mechanical engineering courses has been drawn up. Tribology is an elective

subject for HNC in Engineering, and a Tribology content is included in some CNAA degree courses. The Iron and Steel and Engineering Industry Training Boards include tribological topics in their recommendation for the training of craftsmen. Postgraduate research in tribology, leading to higher degrees, is carried out at several universities; three have Chairs in Tribology. A comprehensive selection of courses and training programmes is also available to industry.

4. Tribology Handbook

This publication⁵, which presents tribological information to industry in a form that is readily accessible and easily understood, fulfills the recommendation of the 'Jost' report that a guide to tribo-engineering design be produced for use by engineering designers, draughtsmen and works engineers.

5. Cost Savings

Whilst it is sometimes difficult to identify and quantify benefits which accrue from specialist advisory services, many case history examples⁶ serve to illustrate the possible returns in relation to the expenditure involved⁷. The Chairman of the British Steel Corporation is on record as stating that savings of £20 million a year could be effected by reducing unnecessary wear. This is equivalent to about £1 per ton of steel produced in the UK. In the first two years of operation the Corporation's own Tribology Section at a cost of approximately £100,000 saved £12 million; reducing wear of hot mill rolls saved £2 million, and improved linings of rod mills saved £100,000 per annum. A Government survey in 1971 showed a net benefit of considerably more than £125,000 on 50 contracts to a value of £16,000 placed on the Swansea Tribology Centre⁸. Similar findings apply to the work of NEL.

6. Current Trends

Economic pressures in the UK have created a swing from routine planned maintenance to failure-prevention maintenance, and thus increasing emphasis is being given to techniques of on-line monitoring, both to prevent the unnecessary dismantling of machinery implicit in the planned periodic maintenance scheme, which experience has

shown can itself contribute to failure, and as a means of predicting deterioration to allow timely remedial action before breakdown. Machines are becoming more complex, and it is not possible to examine in-situ the totally enclosed working parts. However, the lubricant which circulates through the moving parts carries with it evidence of its experience in passage. Careful analysis of the lubricant allows interpretation of the conditions it experienced in passage through the machine.

Wear particles are unique, having individual characteristics which bear evidence of the conditions under which they were formed^{9, 10}. Thus careful examination of the morphology, and determination of the composition of the particles of wear can yield specific information concerning the condition of the moving surface of the machine elements from which they were produced, and allow postulation of the mechanism of their formation and the mode of wear in operation in the system from which they were extracted. Ferrography is a convenient method of extracting particles from a lubricant for analysis¹⁰.

The theme of NEL is now safety and reliability¹¹, and the Ferrographic oil analysis procedure has been developed as a service to British Industry for machinery condition monitoring; excellent results are being obtained.

7. Future Outlook

The era of making advances in engineering by improved design and materials from successful investigation of failures appears to be past. 'On condition' monitoring of expensive machinery to detect failure initiation and to allow a prognostic approach to failure prevention by timely remedial maintenance is now becoming increasingly important and can allow the safe change from expensive planned periodic dismantling of machines for maintenance to the more economic maintenance only when necessary.

As all maintenance is time absorbing and doubly expensive in material wastage and lost productivity, the aim of NEL is the elimination of maintenance by the development of machinery to ensure a maintenance and failure free life of sufficient duration to adequately cover capital expenditure. Particle tribo-analysis by Ferrography is an aid to the design of such machinery^{9, 12}. Information obtained by such analysis can also effect considerable savings by eliminating expensive overdesign incorporating a

a large undesirable safety factor. Adequately condition monitored maintenance free machinery allows savings in buying redundancy for safety engineering.

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- D. "IMPROVED PRODUCT DURABILITY NAVY PROGRAM"
BY A.J. KOURY, NAVAL AIR SYSTEMS COMMAND

A summation of A. J. Koury's presentation is presented below:

Mr. A.J. Koury stated that since material costs represent one of the most important considerations for naval aircraft, components and support equipment, a program is underway concerned with the expeditious implementation of policy aimed at the following:

- (1) impacting life cycle cost by reducing the cost of aircraft maintenance.
- (2) application of new technology to aircraft repair/rework aimed at increasing service life and improving performance/safety/quality.
- (3) conducting the optimum strategy for a more efficient application of materials and processes generated under the Analytical Rework Program (ARP) including methodology for increased utilization of the improved technology during initial manufacture.

He noted that the major challenge encompasses not only the tremendous dollar costs but conservation of vital resources and critical shortages. Accordingly, the Naval Air Systems Command has initiated a multiple thrust program under ARP for employing the latest technology to prevent/control wear, corrosion and stress degradation of naval aircraft structure/components.

One thrust is the exploitation of new approaches to wear reduction. Aircraft include: P-3, A-3, A-5, A-6, A-7, H-53 and F-4. Components include: seals, splines, cable, cutting tools, actuators, cylinders and turbine blades. The Wear Control Program for naval aircraft involves experts from industry, universities, research institutes and government. Briefings and demonstrations covering improved technology are conducted to achieve the earliest implementation. Liaison is maintained with Army, Air Force as well as Navy personnel involved in the repair/rework of aircraft. The interchange of ideas combined with continuous communications between the aircraft RDT&E community, users and suppliers is essential for achieving effective results and such an approach has been followed since the inception of the program. A stronger link to manufacturing technology is needed and work is underway to establish the interface.

Mr. Koury stated that two approaches to wear problems were possible; either accept a certain level of wear and provide sufficient number of parts and manpower to maintain an acceptable level of aircraft availability or reject wear and apply new maintenance technology resulting in improved maintainability, reliability and availability. The latter course represents the policy established by Naval Air Systems Command (AIR-411B4).

He described the results of a survey of aircraft wear which indicated the requirement for an innovative thrust. Accordingly, this meeting represents a first in the economic appraisal of wear.

Mr. Koury then gave numerous examples of the impact of wear from the survey:

- (1) The rework interval on one aircraft type is limited due to control cables and therefore imposing additional reworks.
- (2) Replacement rates of from 75 to 100 percent on components such as bearings, control cables, hydraulic cylinders, valves, bushings and splines.

Examples of the total yearly cost of wear on certain components were also given:

(1) Attack aircraft - Autopilot servovalves	\$ 100,000
(2) Attack Aircraft - Brake wear	2,031,000
(3) Attack Aircraft - Speed brake actuator	91,760

Mr. Koury also presented the following results of the survey which determined the wear costs of one aircraft through one tour of duty. This included both scheduled and unscheduled maintenance costs, as well as, an analysis of the rework costs. The results indicated the following:

Component Maintenance (unscheduled)	\$140/flight hour
Component Maintenance (scheduled)	\$ 67/flight hour
Overhaul:	
Component rework	\$ 20/flight hour
Discrepancies	1.70/flight hour
Tech directives	12.87/flight hour
Materials	3.30/flight hour
Total Cost for Wear	\$245/flight hour
Total Cost for Fuel	\$376/flight hour

Mr. Koury stated that since the establishment of the program, specific studies aimed at the prevention and reduction of wear in aircraft have been initiated. These are listed below:

- Application of wear technology to Naval aircraft
- Application of new and improved solid lubricants

Analysis of miniature bearing maintenance
Naval aircraft control cables
Magnetic separation of contaminants
"State of the Art" roller bearing analysis
Spline wear
Processing of anti-friction bearings
MK-105 hydrofoil erosion/corrosion
Sea floor traversing vehicle
MK-2 torpedo loading tray
Turbine blade erosion/corrosion
Synthetic fibers
Accumulator piston wear
Silicon nitride
Service life improvements covering helicopter transmission
Seal maintenance problems/recommended solutions
Coatings for cutting tools

Mr. Koury highlighted some of the results obtained to date viz:

(1) ANALYSIS OF MINIATURE BEARING MAINTENANCE

A review of the maintenance procedures for instruments employing miniature precision bearings at NARF's resulted in a series of recommendations including:

- a. Reducing "burn-in" requirement from 100 hours to 20 hours.
- b. Reducing the number of lubricants from more than 200 to 3.
- c. Provided critical requirements for up-dating MIL-P-197 to include packaging of precision bearings.

(2) MAGNETIC SEPARATION OF CONTAMINANTS

A study aimed at reducing metal contamination generated in aircraft fluids was conducted with Sala Magnetics. Such contamination accelerates wear, equipment failures, and rework cost. A magnetic separation technique has been demonstrated whereby 90 to 95 percent of metal contaminants were effectively removed.

(3) TURBINE BLADE EROSION/CORROSION (APPLICATION OF SPUTTERING)

This is becoming an increasingly serious problem due to inspection/rework decreasing aircraft availability, as well as, the potential safety factor. In an effort to improve erosion/corrosion resistance of turbine blades, a cooperative effort between NADC/NAPTC resulted in the application of tungsten carbide by sputtering. Resultant blades outperformed a variety of treated and non-treated blades in highspeed erosion tests.

(4) ACCUMULATOR PISTON WEAR

Moisture laden air contained in the catapult and arresting gear systems causes severe pitting and corrosion. High wear due to unit loading on the piston in the accumulator is accelerated by the corrosion. The area of the cylinder in contact with the piston is severely damaged by this combined mechanism.

Results of initial tests show the suitability of polymer powder coating to provide the required corrosion/wear protection.

(5) SPLINE WEAR

The initial effort was to define problem areas and improve maintenance and reliability of aircraft splines. The following example based on application of technology to solve the problem is presented for information on achieving improved durability:

T-63 splines	300% increase in life.
	Normal discarded after
	150 hrs. due to wear

(6) CONTROL CABLES

Due to volume of maintenance actions indicating control cable failures, a processing technique was developed whereby cables were impregnated and encapsulated. Demonstration of this process was conducted at naval air rework facilities and coated cables installed on aircraft. Results after more than 2 years show coated cables continue to perform satisfactorily with no apparent wear or corrosion.

Mr. Koury stated that the major objective of this program is the application of new and advanced wear control technology in Naval aircraft, to prevent catastrophic failures, and to reduce maintenance costs/material and processing requirements.

E. "WEAR CONTROL IN THE BELL SYSTEM"
BY G. KITCHEN, BELL LABORATORIES

The Bell System has only one philosophy, customer service, and all other policies and rules derive from that. Wear control is no exception. Telephone equipment is designed to have the following lives.

Central Office equipment refers to stand-by diesel and turbine generators, rotary motors for dial-tone generation, and all the switching mechanisms used to interconnect local subscribers and telephones all over the world. All of these motors and electro-mechanical switches, such as step-by-step and crossbar, are limited in service life by the wear of bearings and other contacting surfaces. If the design is not sufficiently rugged to last the predicted life, redundant systems are installed to provide the necessary reliability. Some crossbar switches with thirty-five years of service and new lubrication systems were recently evaluated for wear. Prolonged lives in excess of the initial predictions were indicated and they were returned to service. Bearing maintenance and lubrication cycles have been extended and wear reduced by new material applications in motors and generators.

Transmission facilities such as cables are protected from wear during pull-in by specially formulated cable-pulling compounds. Antenna drive gears and bearings such as those used in the original Telstar and the new Domestic Satellite systems were designed to accept both conventional and exotic lubrication systems to provide relatively maintenance free service.

That part of the system that is most visible, customer's apparatus, is designed for twenty years. Most people have seen telephones that have been in service at least that long. Private Branch Exchange (PBX) equipment routinely outlasts its designed life.

Twenty million telephones are removed from service for various reasons each year, are repaired, and are returned to service. Lubrication, friction, and wear problems associated with the gear train and bearings of rotary dials account for about 30 per cent of the dial repairs.

The Bell System recycles significant quantities of its worn parts. From these parts we recover the following.

TABLE IV-2. TELEPHONE EQUIPMENT-SERVICE LIFE

Type	Years
Central Office	40
Transmission	40
Customer's Apparatus	20

TABLE IV-3. MATERIAL CONSUMPTION

Material*	Percent of Annual Consumption
Lead	100
Rhodium	66
Platinum	62
Gold	47
Palladium	32
Copper**	31

*\$900 million of equipment is reworked and reused per year. Approximately 50% of our acrylonitrile-butadiene-styrene (ABS) is now recycled. In addition, pilot plants are now recycling polyvinyl chloride (PVC), and eventually we will recycle about 20 percent of our PVC and about 5 percent of our polyolefins.

**Recycled copper amounts to 81,000 tons.

F. "MAURER FACTOR -- THE NAVY'S ANSWER TO PRODUCTION ENGINE COST ESTIMATION"

BY THOMAS BRENNAN, NAVAL AIR DEVELOPMENT CENTER

1. Introduction

Throughout the years of jet engine procurements, major emphasis has been directed towards the increase of performance of the propulsion system to satisfy the needs for highly sophisticated and effective weapons systems. In search of this increase in propulsion technology, the increase in the state-of-the-art (SOA) to achieve the desired

performance tends to follow the path of most likely consequence, namely Path A in Figure IV-1. Accompanying these strides in SOA and aircraft performance are significant and, in some instances, unacceptable increases in the life cycle cost associated with this system. Confining our discussion in this paper to the propulsion technology and its relative progression paths throughout the past twenty-five years, the trend of Path A has been evidenced quite clearly. The complexity of engines has risen manyfold to pace the nation's military and commercial aircraft market. For such engine manufacturers as General Electric (GE) and Pratt and Whitney Aircraft (PWA), the past twenty-five years have seen military engines grow from 10,000 pounds of thrust for typical post-Korean War fighter aircraft to the high - 20,000 pound thrust class for the F-14B, YF-12 and B-1. Likewise, the commercial transport engines in the same period have increased from 11,000 pounds thrust for the early Boeing 707 aircraft to the 50,000 pound thrust class used today in the 747, DC-10 and C-5A military transport. Accompanying these large increases in propulsion power have been disproportionately smaller increases in weight and volume, giving ample testimony to the SOA progression in specific

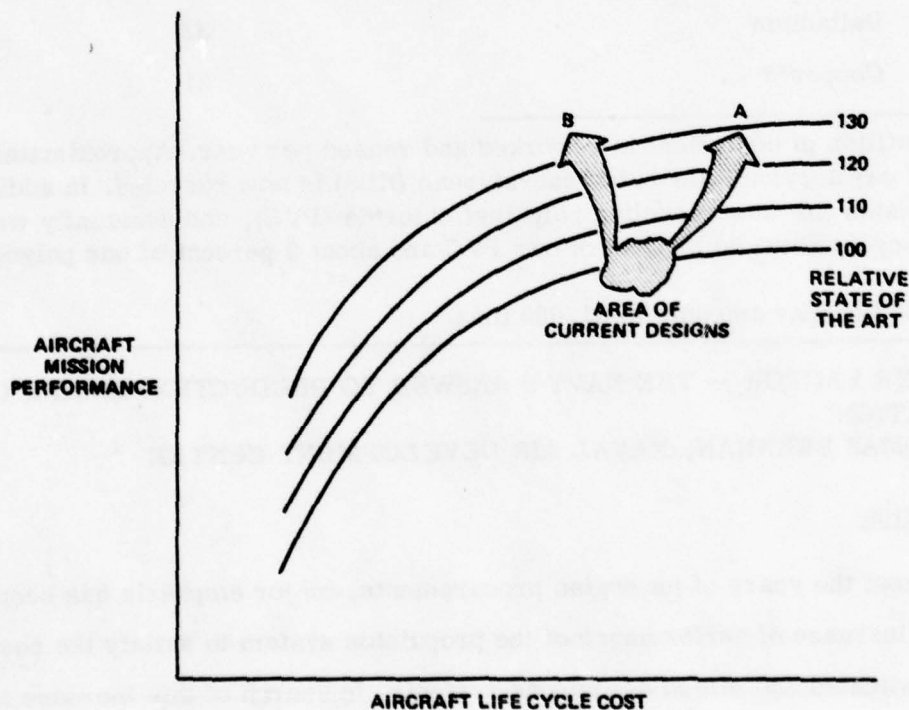


Figure IV-1. Program Alternatives

weights and volumes. The advent of the "million dollar plus" engine, however, indicates that we have paid significantly for our technology.

With the continuing emphasis being concentrated on life cycle costing by the Navy, the potential routes by which we can translate from Path A to Path B are being identified. Production acquisition cost, one element of the complex life cycle costing structure for jet engines, albeit an expensive element, will be discussed in this paper as to the primary cost controllers for producing engines in a production environment and the methods/improvements necessary for lower engine costs.

2. Background and Approach

To properly assess the relationship of cost and engine performance, the Naval Air Systems Command has been sponsoring extensive studies in the basic research of engine costing with the Naval Air Development Center since 1968. To date, results of these studies have provided considerable insight as to the "why and how" of engine costs. These results, however, have been based on a lengthy, developmental approach. During the mid to late 1960's, as higher technology gains began to appear in production engines, it was discovered that the current Navy costing techniques, as well as the costing techniques available from the other services and industry, were inadequate to estimate in advance the impact of this technology on the unit acquisition cost.

3. Rationale

In an effort to uncover the significant areas of propulsion which govern the cost of production aircraft engines, a survey of existing methodologies and cost estimating relationships were investigated and it was concluded that, while no technique could predict advanced technology engine costs accurately using engine parameters as the cost functions, several techniques did allude to the importance and significance of the type of materials being utilized in engines as a probable potential driver. A basic rationale was developed that proposed the cost of an engine, in great part if not entirely, is governed by the type of material as well as the actual weight of the material employed in the manufacture of an engine. This rationale assumes that most of the physical and thermodynamic technology areas associated with engines - compressor stage loading,

maximum turbine temperatures, specific weights, etc. - are closely interrelated with the metallurgical technologies. This assumption is probably more true of the aircraft engine industry than any other aerospace industry because of the severe stress and temperature environment experienced by a jet engine.

4. Maurer Factor

Traditionally, the gas turbine industry has pioneered the high stress/temperature technologies for their specific application. Figure IV-2 shows the change in complexion of engine materials during the past few decades. During the post-World War II and Korean Conflict years, engines were produced from large quantities of carbon and low-alloy stainless steels as well as magnesium and aluminum; in short, the "exotic" nature of the materials used was low. This trend continued until the mid-1950's when the demand for high-Mach speeds and corresponding higher thrusts, efficiencies and temperatures required considerable technology breakthrough to the usage of cobalt-nickel-base alloys as well as titanium materials for weight reduction and strength increases. Inherent in the application of these materials which evolved from this quest for technology is the increase in costs of raw materials and the increase in the difficulty of machining this material.

Initial efforts in defining a material parameter to describe engine costs was done by R.J. Maurer of Naval Air Systems Command in 1966 and 1967. A selective method whereby the raw materials inputted for the manufacture of the engine components was subsequently developed through significant contributions by PWA by classifying the materials into specific categories based on the relative material cost and relative machining cost. Figure IV-3 shows the major classifications of materials representative of all engine components that have evolved through the years. As noted, the conventional materials are the carbon steels, some low-alloy stainless steels, aluminum and magnesium. All titanium alloys were classified under a single category and the more exotic alloys (higher-alloy stainless and various nickel and cobalt base alloys) were categorized into ascending alphabetical groups. The relative material and machining costs were determined by an average of the various forms and processes involved with the various materials. The product of these relative costs then provided a

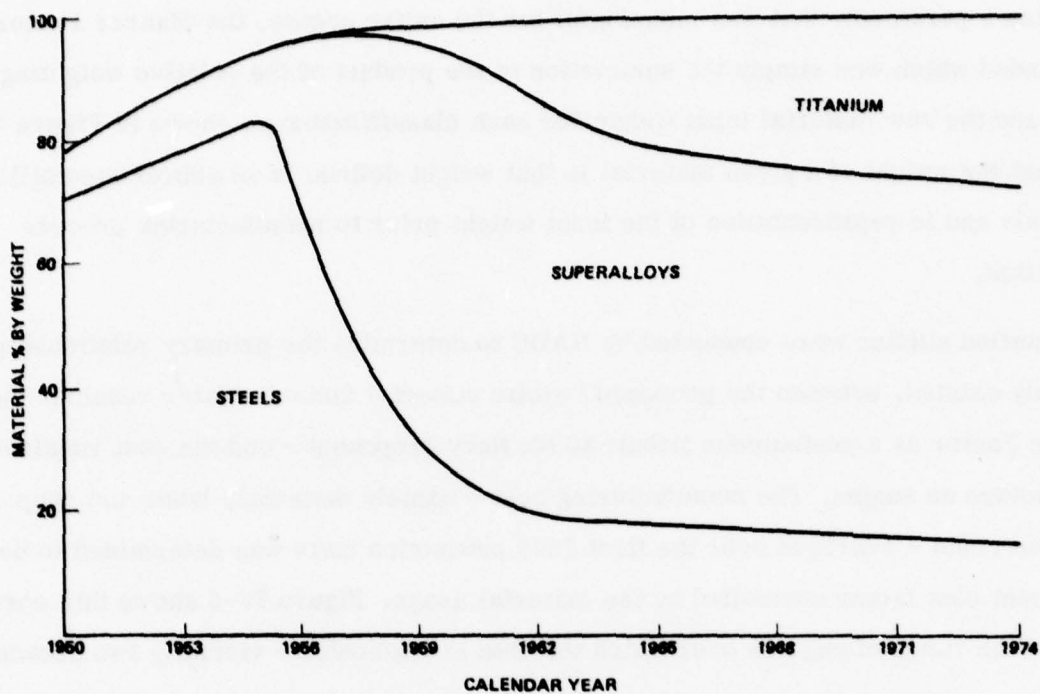


Figure IV-2. Material Trends

	MAJOR CASE, DISC, SPACER SHAFT					
	Ti	A	B	C	D	CONV
RELATIVE MATERIAL COST	7.0	3.4	4.5	5.7	7.10	1.0
RELATIVE MACHINING COSTS	1.5	1.9	3.1	4.0	3.5	1.0
RELATIVE WEIGHTING FACTOR	10.5	6.7	14.0	24.0	29.8	1.0
TYPICAL MATERIALS	6 AL - 4 V 6 AL - 6 V - 2 Sn	17 - 4 PH SS A-286 GREEK ASCOLLOY	HASTELLOY - X HASTELLOY - B INCO - 706	L-605 INCO-718 INCO-625	WASPALLOY RENE-41 ASTROLOY	321 SS CARBON STEEL ALUMINUM

Figure IV-3. Material Classification

relative weighting factor for each of the various classifications as noted in Figure IV-3. To define a parameter that was meaningful for the entire engine, the Maurer Factor was propounded which was simply the summation of the product of the relative weighting factor and the raw material input weight for each classification as shown in Figure IV-4. Note that the weight of a given material is that weight defined in an abbreviated bill of materials and is representative of the input weight prior to manufacturing process application.

Detailed studies were conducted by NADC to determine the primary relationship, if one truly existed, between the proposed "exotic material factor" - later renamed the Maurer Factor as a posthumous tribute to its Navy proponent - and the cost required to manufacture an engine. The manufacturing cost - namely material, labor and shop overhead costs - averaged over the first 1500 production units was determined to be the significant cost factor controlled by the material usage. Figure IV-5 shows this correlation and the range of engines over which the data is applicable - virtually two decades

$$\begin{aligned} \text{MAURER FACTOR} &= \sum_{i=1}^n w_i W_i \\ &= (w_1 W_1 + w_2 W_2 + \dots + w_n W_n) \end{aligned}$$

WHERE w_i IS THE WEIGHT OF THE i TH PART &
 W_i IS THE CORRESPONDING WEIGHTING FACTOR

Figure IV-4. Maurer Factor Derivation

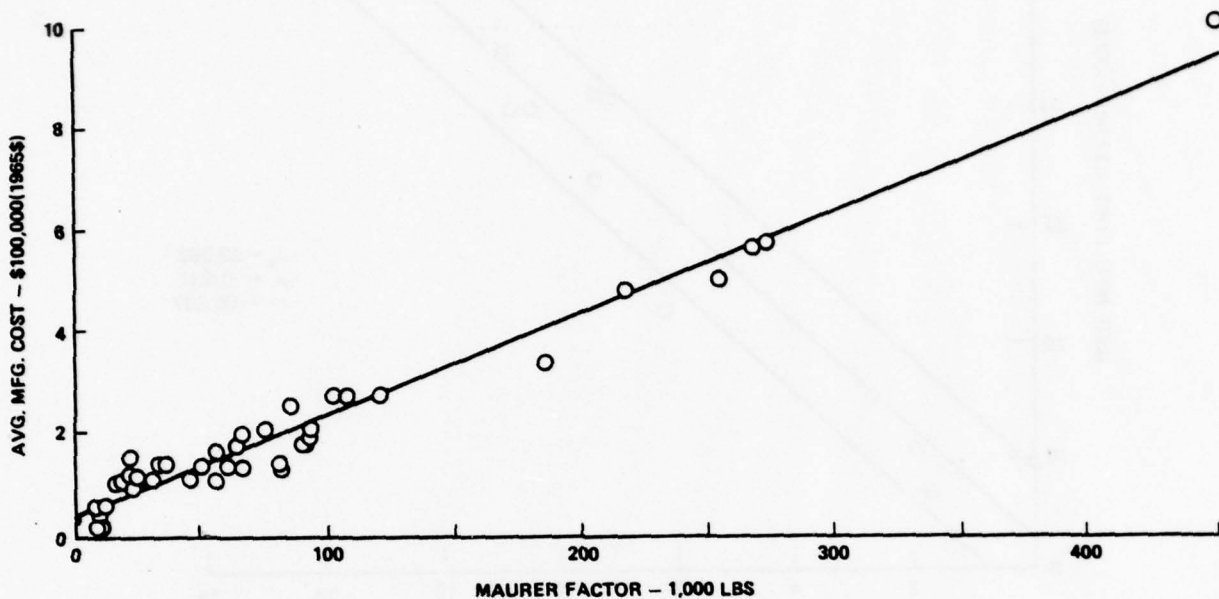


Figure IV-5. Maurer Factor Correlation with Cost

of experience. It should be noted at this point that the correlation shown in Figure IV-5 includes commercial engines as well as military engines and the applicability of the correlation extends to turbofans and turbojets - afterburning and non-afterburning - in addition to turboprop and turboshaft engines. Note also that the statistics representative of the correlation indicate high significance.

Figure IV-5 provided an excellent predictor for engine costs particularly within the high ranges of Maurer Factor, namely that region of the chart toward which advancing technology has tended to drive. Some instances, however, required cost estimation for small, expendable-type engines such as the candidates for the Navy's Harpoon engine, Supersonic Expendable Turbine Engine and the NASA Low Cost Engine. To provide a more detailed resolution of the low-cost end of the curve, all small engines available were compared and the correlation shown in Figure IV-6 was determined for Maurer Factor ranges below 12,000. This correlation and its low intercept value provided a

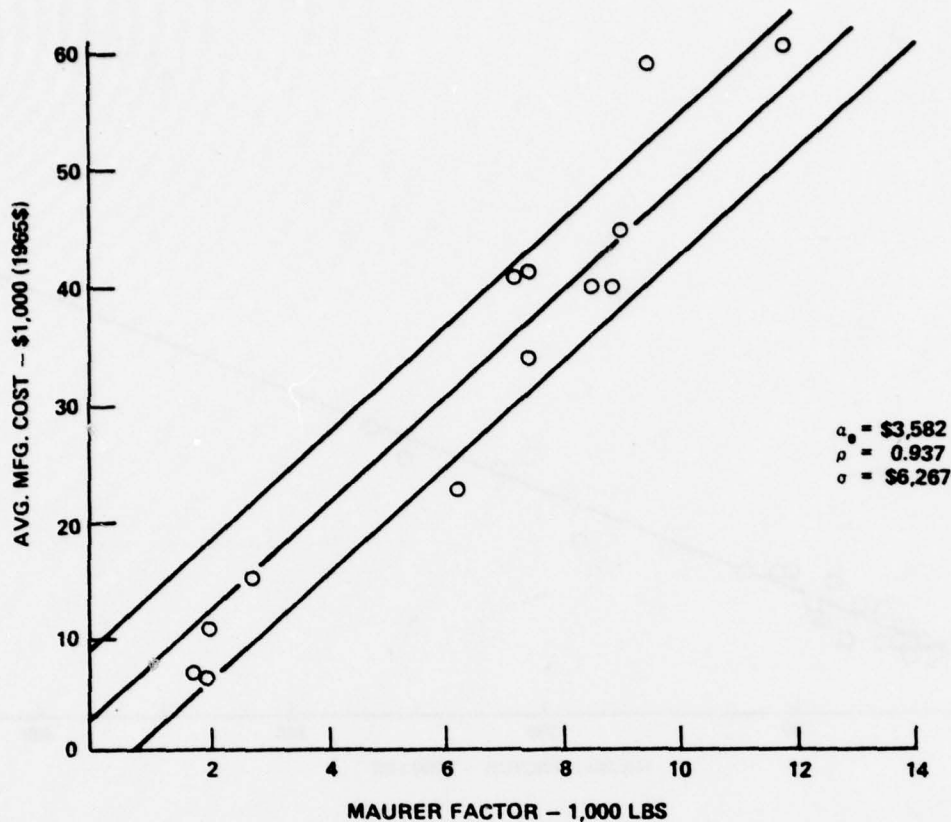


Figure IV-6. Maurer Factor Correlation with Cost for Small Engines

solid foundation to the original assumptions. Figure IV-7 shows the resulting pricing rationale used currently by the Navy for advanced technology engine cost prediction. Much emphasis has been concentrated on the establishment of meaningful escalation rates for labor and material as well as the development of learning theory techniques and applications to the various manufacturers; due to the limited discussion time associated with this paper, these emphasis areas will not be addressed in detail now. The selling price to the government is thus determined by the judicious and rational build-up of material amount and type used to produce the engine.

5. Parametrics

As mentioned previously, no suitable technique could be found which linked engine cost with engine performance parameters. The Maurer Factor, however, showed a relationship exists between materials and cost. Thus, as long as an abbreviated bill of materials was available for an advanced technology engine, an accurate estimate of

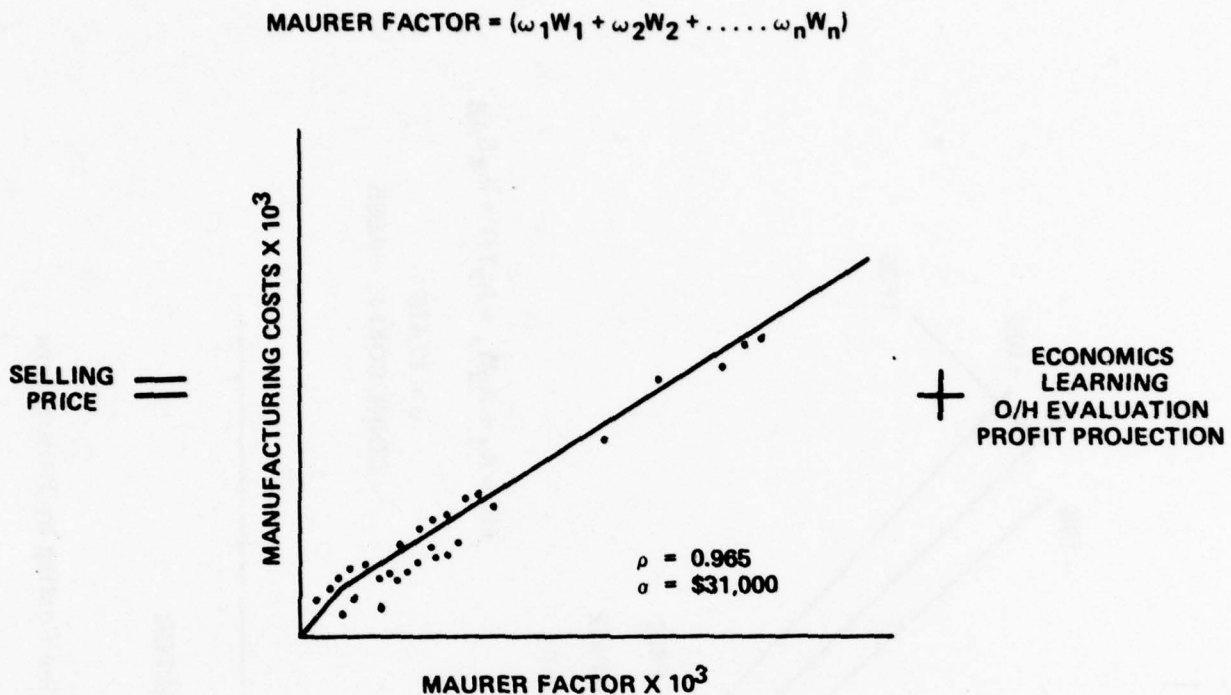


Figure IV-7. Production Engine Costing

its production cost could be made. The availability of design features, not to mention detailed design adequate enough to identify bill of material weights were not always available, however. In fact, many engine proposals tended to be categorized in this latter group, thus highlighting the need for indicators showing what performance parameters are driving the materials. Several techniques were employed for these analyses: regression and historical simulation. There is general familiarization with regression but basically it says that the function which fits all of the data best will be the best predictor. Historical simulation, on the other hand, chronologically samples the data and tests the relationship against the remaining data and says that the independent function that predicts best the data outside its sample is the best predictor. Figures IV-8 and IV-9 provide examples of these two techniques as applied to all turbofan engines. In Figure IV-8, the relative simplicity of the function is of particular interest. As can be seen, the pure linear function involving airflow, turbine inlet temperature and whether or not the engine has an afterburner can be utilized to predict the Maurer Factor (and

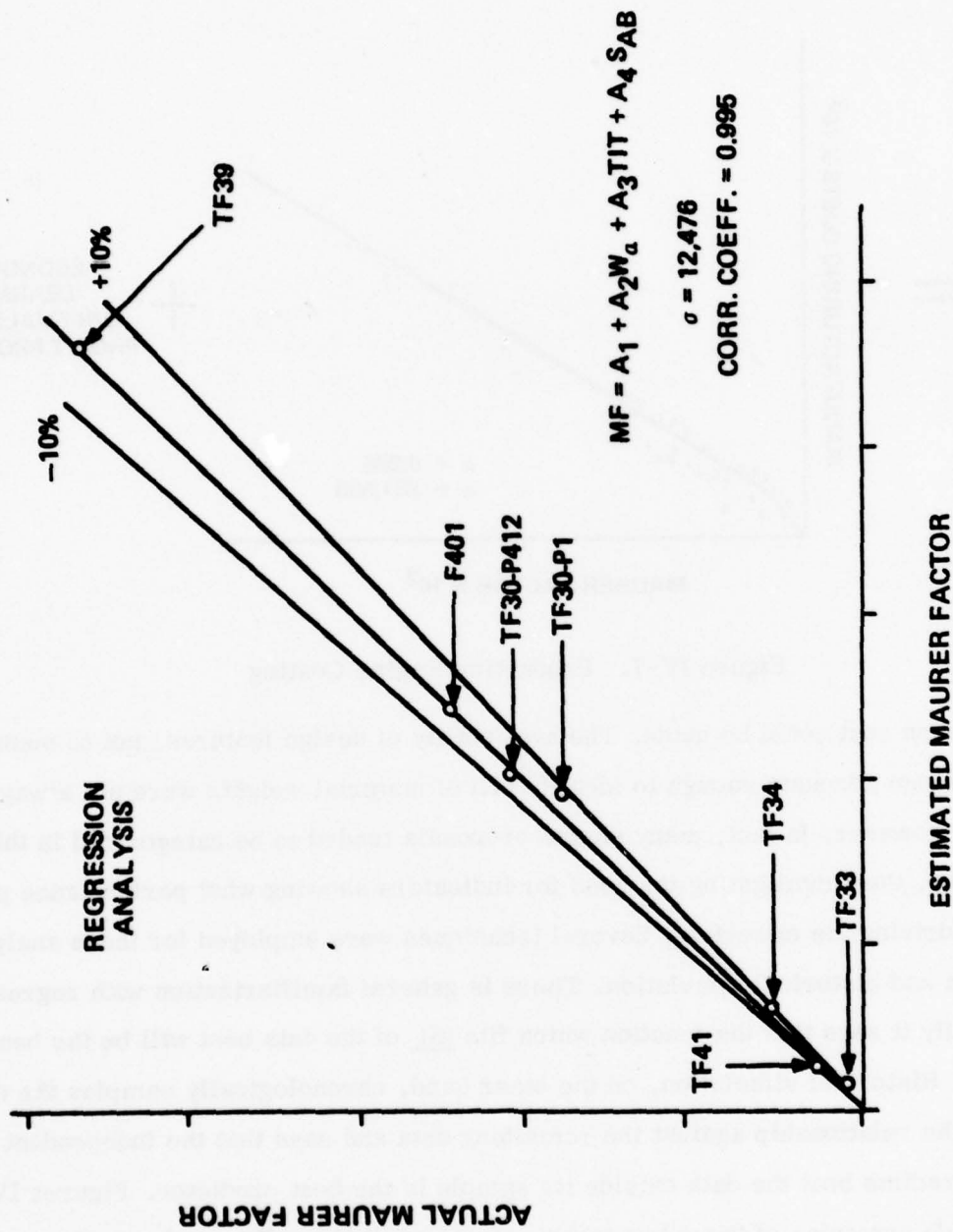


Figure IV-8. Production Engine Costing by Parameters

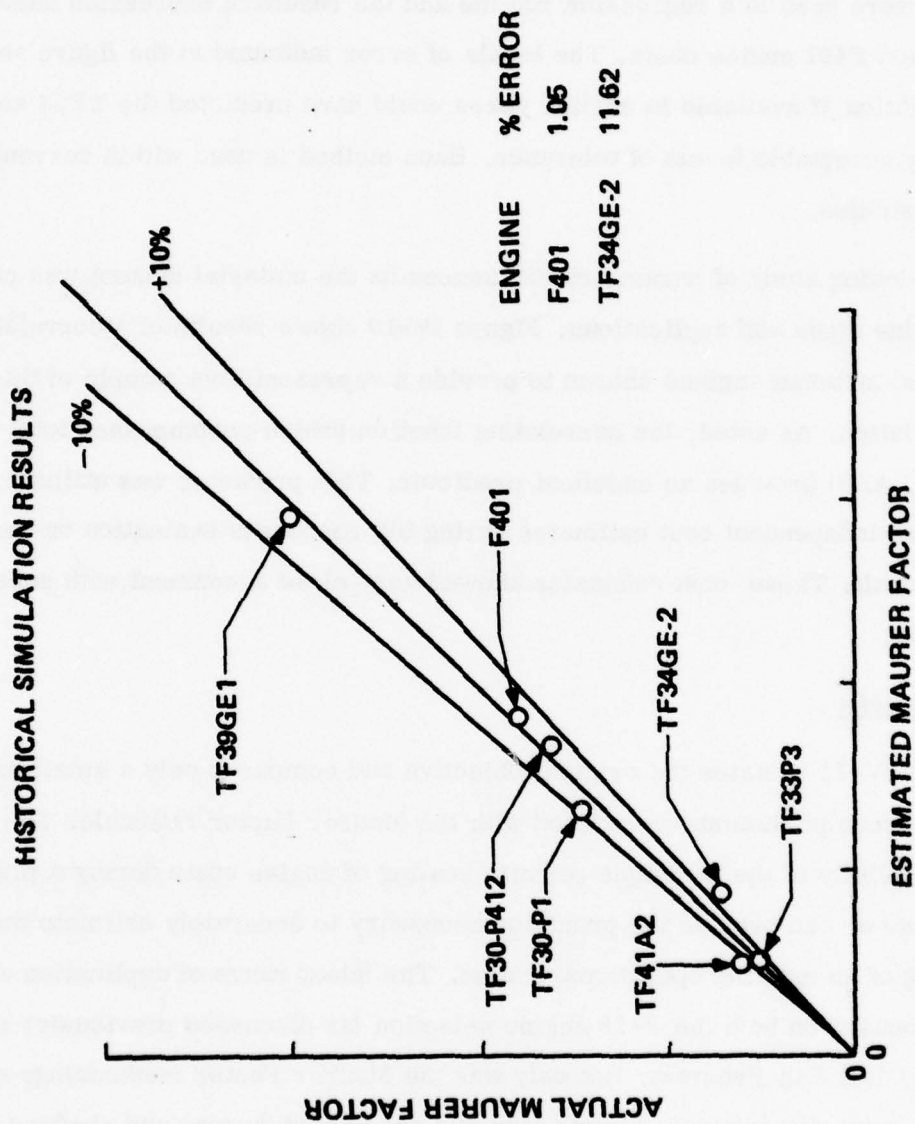


Figure IV-9. Production Costs by Parameters

hence cost) of all the engines within the data range by less than ten percent. Note also the high coefficient of correlation of the predictor. Figure IV-9 shows historical simulation results for the same data. All data points except the last two chronologically (TF34 and F401) were used in a regression routine and the resulting expression used to predict the TF34 and F401 engine costs. The levels of error indicated in the figure show that this correlation if available in earlier years could have predicted the TF34 and F401 within very acceptable levels of tolerance. Each method is used within current Navy analytical studies.

A continuing study of parametric influences on the material content was continued for all engine types and applications. Figure IV-10 shows results of a correlation of 15 turbojet and turbofan engines chosen to provide a representative sample of this mixed cycle population. As noted, the correlating function (which encompasses total airflow, BPR, TIT, A/B) provides an excellent predictor. This predictor was utilized specifically to formulate independent cost estimates during bid responses evaluation on the NACF (F-18) aircraft. These cost estimates showed very close agreement with submitted contractor bids.

6. Applications

Figure IV-11 restates the original objective and compares only a small number of the actual accomplishments associated with the Maurer Factor rationale. The fundamental simplicity of the technique permits scaling of engine costs during a preliminary design phase or can provide the precision necessary to accurately estimate the cost of an uprating of an existing operational engine. The latest range of application of the model has been focused on both the F-18 engine selection (as discussed previously) and the NASA/Navy Lift Fan Program. Not only was the Maurer Factor methodology capable of estimating costs for engines, remote fans and associated ducting and shafting with close compatibility to contractor efforts, but the potential cost impact of redesign of the fans was investigated, relayed to the manufacturers with significant changes and cost savings in the engine/fan resulting. As shown by Figure IV-11, design-to-cost and the Maurer Factor are synonymous in engine costing.

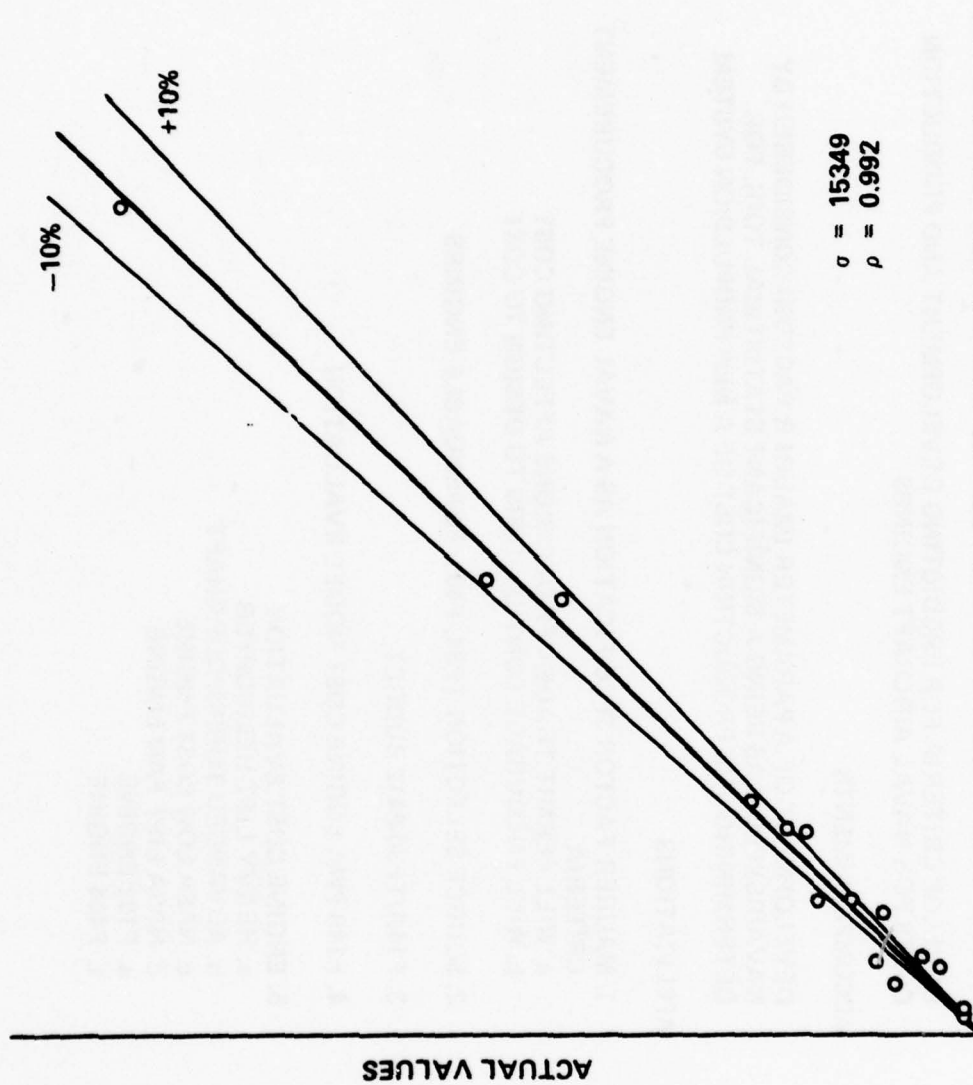


Figure IV-10. Maurer Factor Study

OBJECTIVE

DEVELOP CRITERIA FOR PREDICTING DEVELOPMENT AND PRODUCTION COSTS FOR NAVAL AIRCRAFT ENGINES

ACCOMPLISHMENTS

DEVELOPMENT OF A PARAMETER (MAURER FACTOR) CONSIDERED BY NAVAIRSYSCOM AS BEING A SIGNIFICANT STATISTICAL TOOL FOR DETERMINING THE PRODUCTION COST OF A NEW PROPULSION SYSTEM

APPLICATIONS

1. MAURER FACTOR SPECIFICATION AS A NAVAL ENGINE PROCUREMENT

CRITERIA

- a. WILL PERMIT TRADE-OFF DECISIONS AFFECTING COST
- b. WILL ENCOURAGE CONTRACTORS TO DESIGN TO COST

2. SOURCE SELECTION TF34, F401, EXPENDABLE ENGINES

3. F14A/TF30-P412 BUDGET

4. F14B PWA ENGINE COST MODEL EVALUATION

5. ENGINE COST EVALUATION

- a. HEAVY LIFT HELICOPTER
- b. ADVANCED TURBOPROP/SHAFT
- c. NASA LOW COST ENGINE
- d. NASA LIFT FAN ENGINE
- e. F101 ENGINE
- f. F404 ENGINE

Figure IV-11. Engine Cost Study

7. Future Design Influences

As a final summation on the merits of a material approach to engine costing, its impact on future designs and manufacturing is discussed. There are two apparent means by which lower engine costs are possible. The first involves the research and eventual production usage of other advanced materials capable of surviving in the high stress and temperature environment, yet providing lower material and machining costs. The obstacle to this route, however, has been shown by history to be opposing in nature and thus is considered a highly unexpected breakthrough area. The other route, however, is more visible. Shown in Figure IV-12 is the material utilization of seven randomly selected engines. For the engine overall, more than five pounds of raw material is required to produce a pound of finished product. Similar material utilization for the various material categories are also shown with the low utilization rates of the more exotic materials of special significance. The message ringing clear from these factors is that the paths to cost reduction in engines is evident - reduce the scrap rate and the price of engines will reduce accordingly. Maurer Factor has shown us that material is money and, considering the enormous amount of funds expended in production engines each year, the potential for cost savings as well as material conservation may provide a step-jump to Path B of Figure IV-1. Technology increases in the methods for forming and processing materials will significantly increase the utilization rate, and a recommended goal for the next ten years is reduction of the current scrap rate by 50 percent. It is considered incumbent upon both government and industry together to seek solutions to this goal because the expected return-on-investment to both of us is well worth the effort.

G. "NATIONAL SCIENCE FOUNDATION ACTIVITIES IN TRIBOLOGY"

BY MICHAEL P. GAUS, HEAD, ENGINEERING MECHANICS SECTION, NATIONAL SCIENCE FOUNDATION

The National Science Foundation was established by an Act of Congress in 1950 with several subsequent amendments which authorized the Foundation to initiate and support basic scientific research and programs to strengthen scientific research potential in the mathematical, physical, medical, biological, engineering, social and other sciences

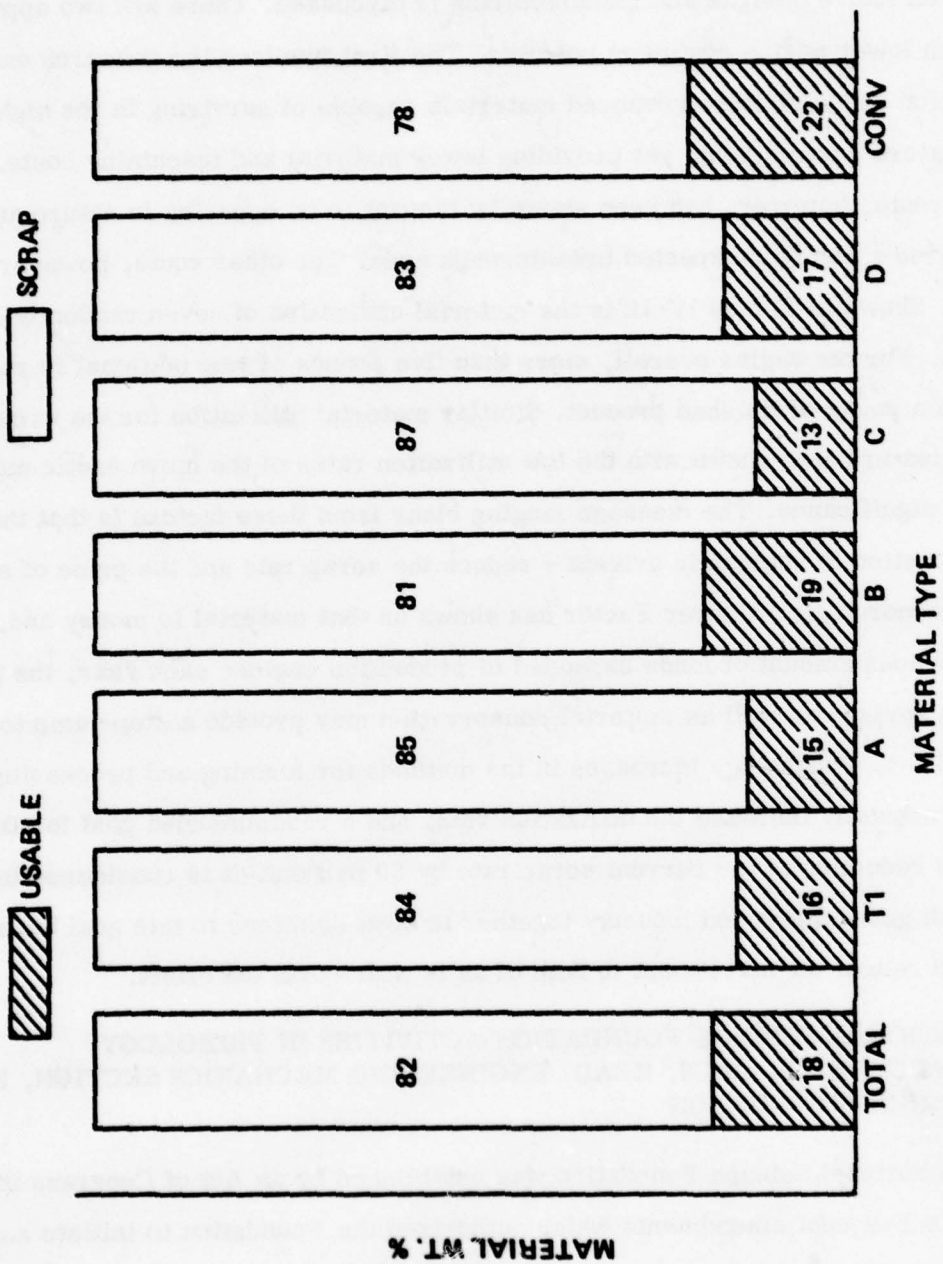


Figure IV-12. Design Influences Influencing Manufacturing Technology

to award scholarships and graduate fellowships, to foster interchange of scientific information between the United States and foreign countries, to foster the development and use of computer and other scientific methods and technologies and to evaluate the status and needs of the various sciences as evidenced by programs, projects and studies undertaken by agencies of the Federal Government, by individuals and by public and private research groups. The act as amended allows the Foundation to support applied research at academic and nonprofit institutions and under certain special circumstances to support applied scientific research relevant to national problems involving the public interest through other appropriate organizations. The Foundation is itself specifically prohibited from operating any laboratories or pilot plants.

This background information is given to help place Foundation research activities in perspective as compared to other Government agencies. In carrying out its functions, the Foundation is organized into a series of directorates which report, through their Assistant Directors, to the Deputy Director and Director of the Foundation. This organizational structure is shown in Figure IV-13 along with the estimated budgets for FY 1976. Tribology research receives support from several different organizational units of the Foundation and will be specifically discussed later. The general thrust of Foundation activities are to generate a new or improved knowledge base, which may be subsequently utilized by groups having an operational responsibility, with heavy emphasis on the support of longer-range type of research. Because many other agencies also conduct significant research programs, Foundation support often acts as a balance wheel for some research areas. There is heavy emphasis in Foundation programs on support of academic research programs.

Among the various directorates of NSF, tribology related research receives some support primarily from the Directorate of Mathematical and Physical Sciences and Engineering and to a lesser degree from the Research Applications Directorate. Some of these activities will be discussed to illustrate NSF supported research related to tribology.

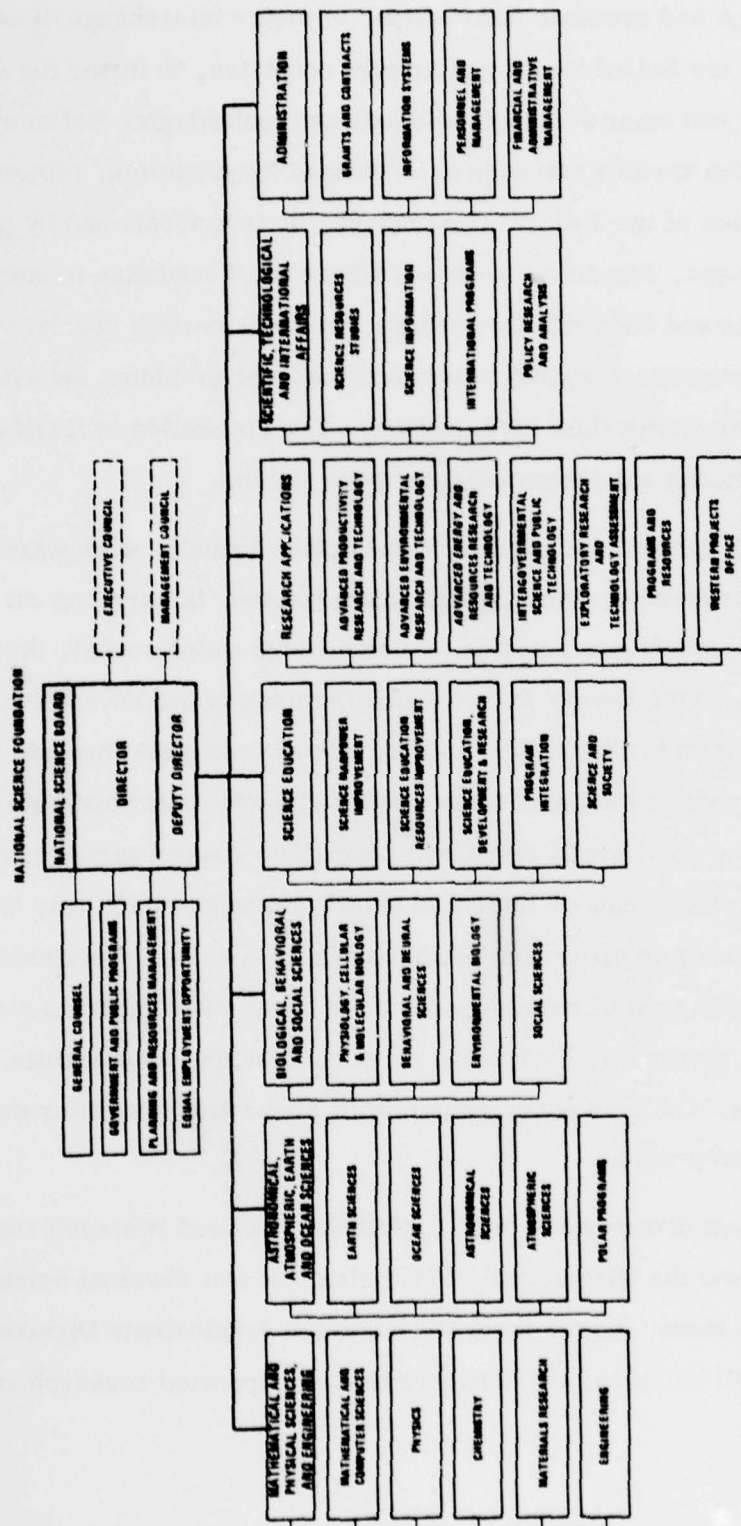


Figure IV-13. National Science Foundation

1. Research Applications Directorate

The Division of Exploratory Research Problem Assessment supported two studies conducted by Professor Herbert Hollomon of MIT on the subject of increasing productivity for servicing consumer durables. A part of this study was aimed at assessing the durability of present consumer durables. Funding for wear related research is about \$31,000 per year.

2. Mathematical and Physical Sciences and Engineering Directorate

Tribology related research is supported through two Divisions: the Engineering Division and the Division of Materials Research. The organization of these divisions is shown in Figure IV-14.

a. Division of Materials Research

The tribology related support in this division is for studies in ultrahard materials and to gain a better knowledge of fretting and impact and wear behavior of metal surfaces as related to microstructure of the material. Typical examples of research supported are a project by Professor J. Larsen-Basse of the University of Hawaii on Abrasion of Metals. Professor M. C. Shaw of Carnegie-Mellon University is studying the Performance of Abrasives in Fine Grinding which relates to the type of surface finish which can be obtained in manufacturing processes. Professor D. Basu of Lehigh University is studying Mechanisms of Wear and Performance of Multicomponent Ceramic Oxide Cutting-Tool Materials which have great potential for increasing productivity in cutting operations. Professors N.H. Cook and N. P. Suh of MIT are studying the Enhancement of Cemented Carbide Tool Properties also with the objective of reducing wear rate of tools and improving productivity and product quality. Professor E. Rudy of the Oregon Graduate Center is studying Hard and Wear-Resistant Materials. Professor M. Barash of Purdue University is studying Thermoelectric Wear of Tools. Dr. M. Hoch of the University of Cincinnati is studying the Failure Mechanisms in Superhard Materials Used to Cut Superalloys including considerations of the wear mechanisms. A summary of research related to hard materials is contained in a workshop report entitled "NSF

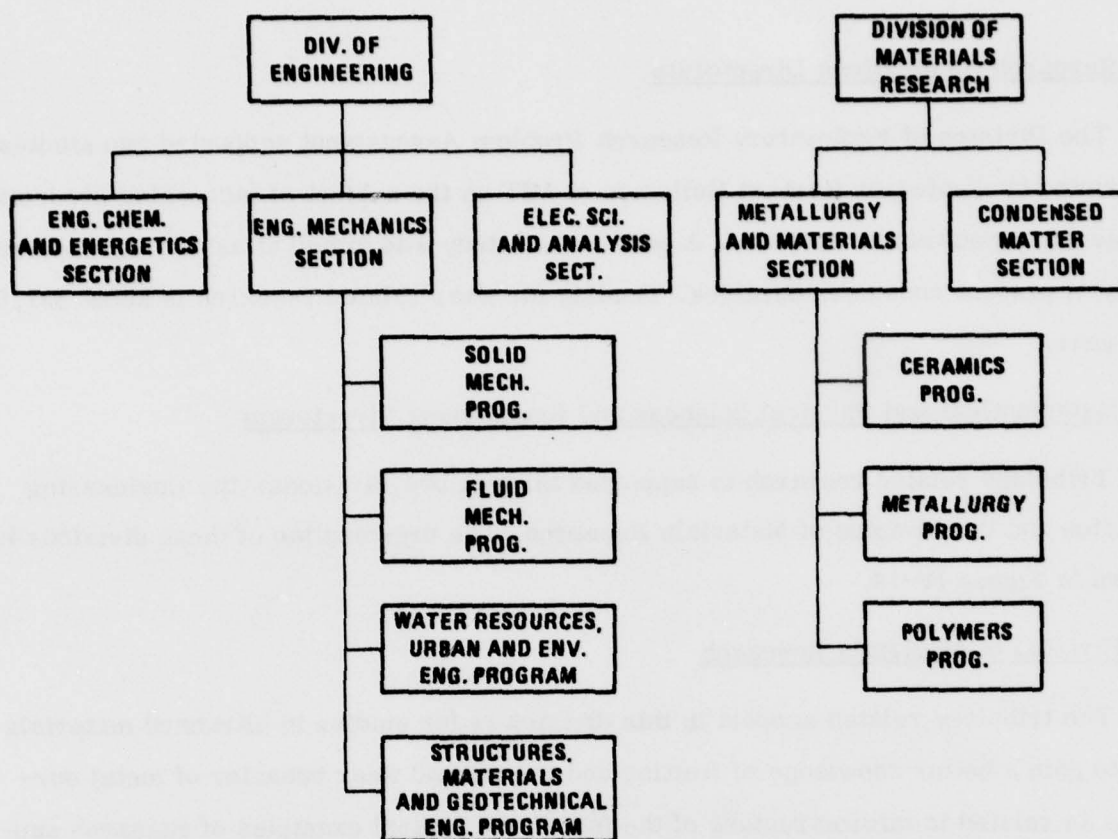


Figure IV-14. Divisions in NSF that Support Tribology Related Research

Hard Materials Research - Volume Four, 1975" prepared by the University of Cincinnati. Support for wear-related research in materials is at an annual rate of about \$200,000 per year.

b. Division of Engineering

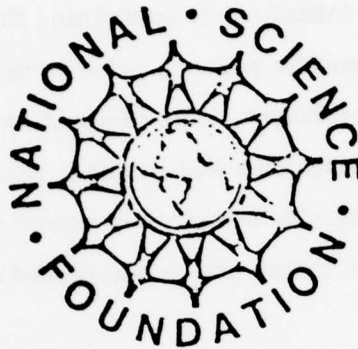
The Engineering Division has provided sporadic support for tribology related research at universities since its establishment, in response to unsolicited proposals submitted to the division. This type of activity primarily falls within the scope of the Engineering Mechanics Section, one of three sections, in the Division. Due to what appeared to be an increased interest on the part of the university-community in the general areas of mechanical behavior, mechanical processing, noise and acoustics, energy conservation, nondestructive testing and other related activities, a Mechanical and Industrial Technology Program was established in the Engineering Mechanics Section about three years ago to provide an identifiable point of contact for researchers in these fields.

In order to assess research opportunities in various areas and to draw attention to areas where insufficient research activity seems to be taking place, the NSF Engineering Division has for a number of years supported university-industry workshops to examine specific technical areas. These workshops typically involve 30 to 40 people representing universities, industry and government. A typical workshop will last two days and usually devotes its initial effort to defining the "state-of-the-art" through presentations prepared by specific persons prior to the workshop. After the present status of the field has been evaluated, time is spent on discussing and attempting to define future trends and opportunities and possibly relative priorities for research. The output of the workshop is generally a workshop report on proceedings which is mailed to all engineering schools in the United States and placed into NTIS to make it available to interested persons.

In calendar year 1974 a number of persons indicated to the Mechanical and Industrial Technology Program that the field of Tribology was one of great importance due to its relation to energy conservation and to product durability and performance. In order to better assess research opportunities in this field, support was provided for a Tribology Workshop. This workshop was organized by Professor H.S. Cheng of Northwestern University, Professor Frederick F. Ling of Rensselaer Polytechnic Institute and Professor Ward O. Winer of Georgia Institute of Technology. Professor Cheng handled workshop planning, Professor Ling served as editor for the proceedings and Professor Winer served as director of the workshop sessions. The workshop was held in April 1974 at Georgia Institute of Technology and resulted in a 677 page Proceedings. (Unusually large for such a workshop.) This Proceedings is available from NTIS - Accession number PB 241 253/AS. The report cover and table of contents are shown in Figures IV-15 and IV-16.

Following this workshop a research request was submitted by Professors Cheng, Ling and Winer to conduct a coordinated research program on Mechanical Equipment Reliability Through Tribology. After the usual peer review evaluation of the proposal, support was provided for the research effort. The research effort is divided into 3 phases: elasto-hydrodynamic lubrication, rheology of lubricants and lubricated surfaces, and wear

Proceedings of THE TRIBOLOGY WORKSHOP



**Sponsored by
The Industrial Technology Program
Mechanics Section
Engineering Division
National Science Foundation**

April 1974

Workshop Committee:

**Herbert S. Cheng, Northwestern University
(Chairman of Workshop Planning)**

**Frederick F. Ling, Rensselaer Polytechnic Institute
(Editor of Proceedings)**

**Ward O. Winer, Georgia Institute of Technology
(Director of Workshop Sessions)**

Figure IV-15. Proceedings of The Tribology Workshop

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control as shown in Figure IV-17. An interesting feature of this particular research program is the use of an Industrial Advisory Board to both provide advice and to facilitate the transfer of technology from research to groups who would be concerned with its application. Support for tribology research in FY 1975 totaled approximately \$480,000. In 1975 the Mechanical and Industrial Technology Program was abolished as announced in the February 1975 NSF Bulletin, Volume 2, Number 6 and any future support for tribology research in the Engineering Division will have to come from the remaining programs in the Engineering Mechanics Section.

H. "TRIBOLOGY AT THE OFFICE OF NAVAL RESEARCH"
BY DR. R. S. MILLER, OFFICE OF NAVAL RESEARCH

The Tribology Research and Development Program at the Office of Naval Research has the objectives of providing fundamental understanding and technology necessary to minimize wear in Naval equipment. The approach of the program which is jointly funded by the Research Directorate (Dr. E.I. Salkovitz, Director Material Science Division)

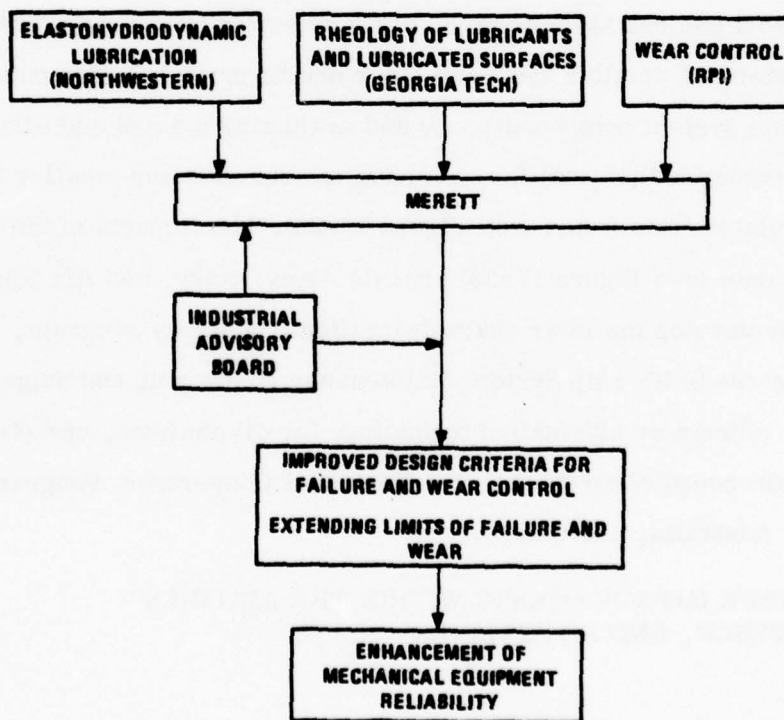


Figure IV-17. Merett Project Objectives

and the Technology Directorate (Mr. D. C. Lauver, Director Technology Projects Division) is three fold. (Figure IV-18)

The surface separation and optimization program has the objective of understanding elastohydrodynamic surface separation and traction phenomena so that surface interaction in elastohydrodynamic bearing and gear contacts can be minimized. The concerned individuals, their affiliations and the appropriate total level of FY 76 funding for these efforts are listed in Figure IV-19. The wear minimization program has three objectives. (Figure IV-20). The first objective is to characterize wear surface and wear particles so that the information can be used immediately to diagnose the mechanisms of wear in Naval equipments. The longer range and the second objective is to understand the fundamental mechanisms of wear so that materials may be eventually specified that offer the potential of minimum wear. The contractors involved in the wear characterization and minimization program are listed in Figure IV-21. Both Professor Suh's and Westcott's work are supported by DARPA. (C. Martin Stickley, Director Material Science Division). The wear particle effects and removal program is also a part of the wear minimization effort and has the objectives of (1) determining the magnitude of the harmful effects micrometer and smaller wear and other debris particles have on the life of hydraulic and lubrication system components, (2) and evaluating a novel and effective technique (high gradient magnetic filtration) for removing micrometer and smaller ferro or paramagnetic particulates from fluids (see Figure IV-22). The impacts of the wear minimization program to date (see Figure IV-23) are: (1) Army, Navy, and Air Force development efforts to further develop the wear characterization technology program, (2) the use of the technology by the SSBN Ship System Maintenance Monitoring and Support Office, (3) a reasonable adjunct or alternative technology for oil analysis, and (4) a complimentary research program coordinated through the Technical Cooperation Program between the U.S., England, Australia, and Canada.

I. "MAINTENANCE IMPROVEMENTS WITHIN THE AIRLINES"
BY T. MATTESON, UNITED AIRLINES

1. Abstract

There has been a startling metamorphosis in maintenance programs for air transport airplanes in the past 12 years. Formerly, these programs were based on an unproven,

PHILOSOPHY

OPTIMIZE SURFACE SEPARATION

MINIMIZE WEAR

CHARACTERIZE WEAR

Figure IV-18. Wear Prevention/Control R&D at ONR

EHD CONTRACTORS

MONTROSE	CATHOLIC UNIV.
MACEDO	CATHOLIC UNIV.
CAMERON	IMPERIAL COLL.
KANNEL	BATTELLE COLUMBUS
MONIZ	NAVAL RESEARCH LAB
MILLER, FRITZ	ONR

FY76 INVESTMENT 150K

Figure IV-19. EHD Contractors

WEAR MECHANISMS THROUGH
 WEAR SURFACE CHARACTERIZATION
 WEAR PARTICLE IDENTIFICATION
 WEAR PARTICLE EFFECTS
 WEAR PARTICLE REMOVAL

Figure IV-20. Wear Minimization R&D

WEAR MECHANISM R&D

SUH

RUFF

GOLDBLATT

REEVES

WESTCOTT

KOMANDURI

THIRUVENGADAM

MIT

NBS

EXXON

MISSOURI

TRANSONICS

CARNEGIE-MELLON

CATHOLIC

DELAMINATION WEAR

SURFACE CHARACTERIZATION

LUBRICANT INDUCED WEAR

FRETTING WEAR

FERROGRAPHY

GALLING WEAR

CAVITATION WEAR

FY76 INVESTMENT 350K

FY 76 INVESTMENT 350K

Figure IV-21. Wear Minimization Program

WEAR PARTICLE EFFECTS/REMOVAL

FITCH	OKLAHOMA	HYDRAULIC SYSTEM SENSITIVITY
OBERTEUFFER	SALA MAGNETICS	HIGH GRADIENT MAGNETIC SEPARATION

FY 76 INVESTMENT 180K

Figure IV-22. Wear Particle Effects/Removal

TECHNOLOGY IMPACT

UTILIZATION

R&D

ARMY, NAVY, AIR FORCE
TECHNOLOGY COORDINATION PROGRAM
(U.S., ENGLAND, AUSTRALIA, CANADA)

OPERATIONAL COMMANDS

SSBN'S

ASSESSMENT

OIL ANALYSIS PROGRAM IN DOD

Figure IV-23. Technology Impact

but universally accepted intuitive model which ascribed great value to scheduled overhauls as a means for ensuring the highest level of operating safety. Knowledge obtained from careful analysis suggested the application of a decision tree technique for determining preventive maintenance requirements. This technique has proved its effectiveness on the 747 and DC-10, the first new airplanes to which it was applied.

2. Objectives of a Maintenance Program

A maintenance program exists:

- a) To prevent deterioration of the inherent levels of safety and reliability associated with hardware design.
- b) To do so at minimum total cost.

Opinions differ about the effectiveness of maintenance in improving reliability above inherent design levels. However, I believe the more qualified opinion is that:

- a) "More maintenance" does not yield reliability levels higher than are inherent to a particular design.
- b) Basic changes in design are required to cause an increase in inherent reliability.

3. Traditional Ideas

Much of what we believe to be true is based on traditional ideas. These ideas, or at least some of them, are originally based on fact. The English writer "Junius" whose real identity still escapes us, expressed the effects of time on facts much better than I when he wrote, "What yesterday was fact, today is doctrine". Let's look at 3 ideas and their application to early experience with airplanes:

- Mechanical parts wear out,
- Wearouts cause failures, and
- Failures degrade safety.

These 3 ideas are those that are intuitively relied upon when one believes that preventive maintenance increases safety. The first aircraft accident in which a passenger died occurred at Fort Meyer, Virginia, in 1908 when Lt. Selfridge was killed in a crash caused by a propeller failure in an airplane piloted by Orville Wright.

The cause for this crash is consistent with these ideas, so these ideas were certainly facts at that time, for that airplane.

These ideas support the belief that preventive maintenance can increase safety. Any scheduled maintenance task that would have prevented wearout of the propeller or removed it before it failed would have certainly increased the safety of the Wright airplane that crashed at Fort Meyer. But what were that airplane's design characteristics?

It was a very primitive machine, essentially devoid of redundancy, requiring that every part perform as expected in order that it stay in the air. It was the design of that airplane that made facts of these 3 ideas.

Experience with early aircraft supported these conclusions:

- Safety and reliability are highly correlated,
- Reliability degrades with increasing age, and
- There is a finite age beyond which each device is unairworthy.

The first of these is based on the idea that failures of components or parts of an airplane have a direct, adverse effect on operating safety. The second of these is based on an idea that the so-called "bath tub curve" shown in Figure IV-24 is generally, if not universally, applicable.

In the current American Federal Aviation Regulations and associated advisory material, we still have a lot of words that are based on these conclusions.

For example:

"...the basic principle followed by the Administrator will be that the inspections, checks, maintenance and overhaul be performed at times well within the expected or proven service life of each component of the aircraft."

Now let's examine the effect of design on safety and reliability in a more general way.

4. Safety and Reliability and Their Relationship to Design

The safety and reliability of an aircraft are both a function of its inherent design characteristics. In the eyes of the layman this common relationship of safety and

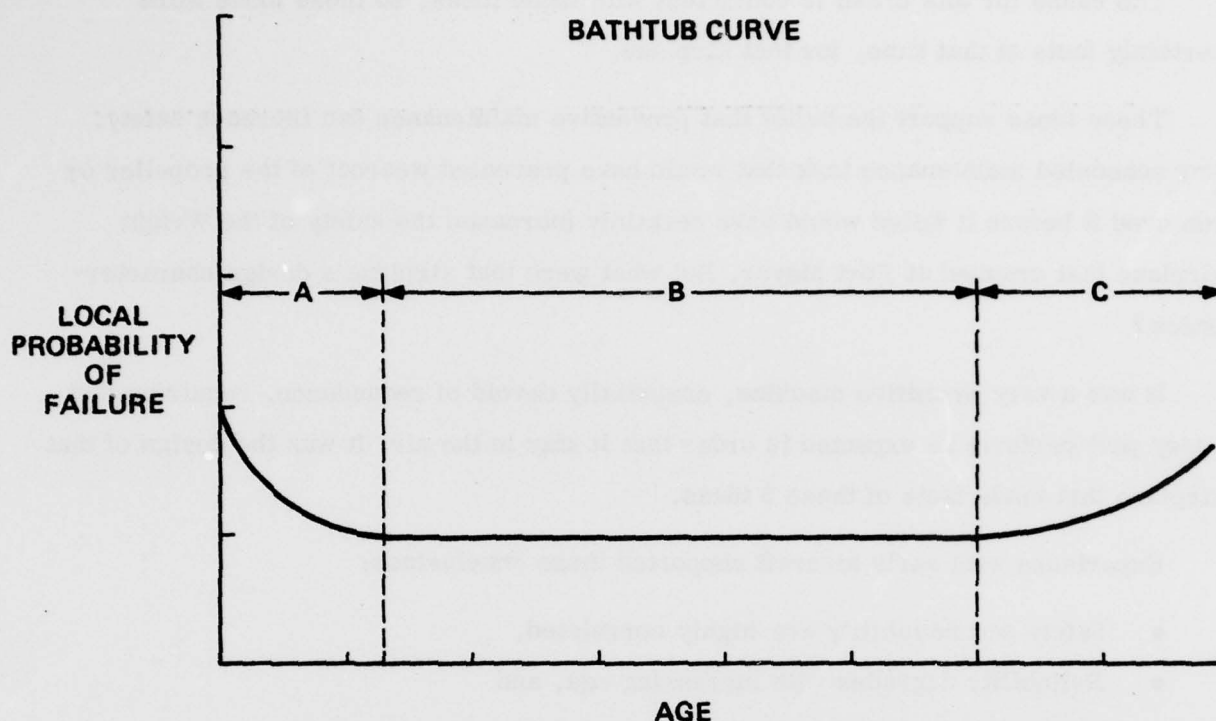


Figure IV-24. Bathtub Curve

reliability to design leads to the apparently logical conclusion that safety and reliability are necessarily closely related. This is not so. Another factor controls this relationship. This factor is the ability of a design to retain its essential functions, even though failures occur. Although this quality may be obtained by a number of techniques, let us simply call it "redundancy".

Since the era of Bleriot and the Wright Brothers, tremendous increases in the efficiency of aircraft have occurred. These increases in efficiency have made it possible for an aircraft to carry much more than the pilot and fuel for a short flight as was then the case. It is this increased efficiency that has made aircraft economically useful. Much of this increased efficiency has resulted in increased lift. This has been allocated in many ways - extra fuel, payload, passenger accommodations, instruments and redundant systems are examples. Today's transport aircraft has more of its empty weight allocated to redundancy than any other aircraft type. The result, of course, is an extremely high level of safety that is achieved by ensuring that hardware failures do not

affect safety and high schedule reliability that is achieved by permitting a trip to continue to its destination irrespective of enroute hardware failures.

The safety and reliability of each successive generation of transport aircraft has improved. The government design requirements and the specifications of the airlines and the manufacturers have repeatedly been changed to ensure that a portion of the benefits of improving the state of the art of aircraft design are allocated to improved safety and reliability. The result is a level of safety and reliability that is second to none in the world.

Although operating safety and schedule reliability have reached extremely high levels, it is important to recognize that literally hundreds of thousands of malfunctions are experienced each year by air transport aircraft. (See Figure IV-25).

Obviously, something very important has happened since the days when a single part or component failure had a strong likelihood of causing a crash. In the past 12 year's careful study, we have learned a lot about this "something". We now have a lot of modern ideas.

5. Modern Ideas

The late William C. Mentzer, United Air Lines' former Senior Vice President-Engineering and Maintenance provided the spark for our discoveries in the late fifties by asking, "Why do we do scheduled maintenance?"

"It is implied that an instance of environmental stress which exceeds the failure resistance of an item at a particular time constitutes failure of that item at that time."

Figure IV-26 illustrates these ideas. In this example, the failure resistance decreased with age, and there is an increasing likelihood of failure with age. This example is strictly applicable to single-celled or simple devices or to specific modes of failure of complex devices. Figure IV-27 illustrates the effect of effective periodic preventive maintenance in this case. Some typical real examples are lubrication of the landing gear and replacement of tires.

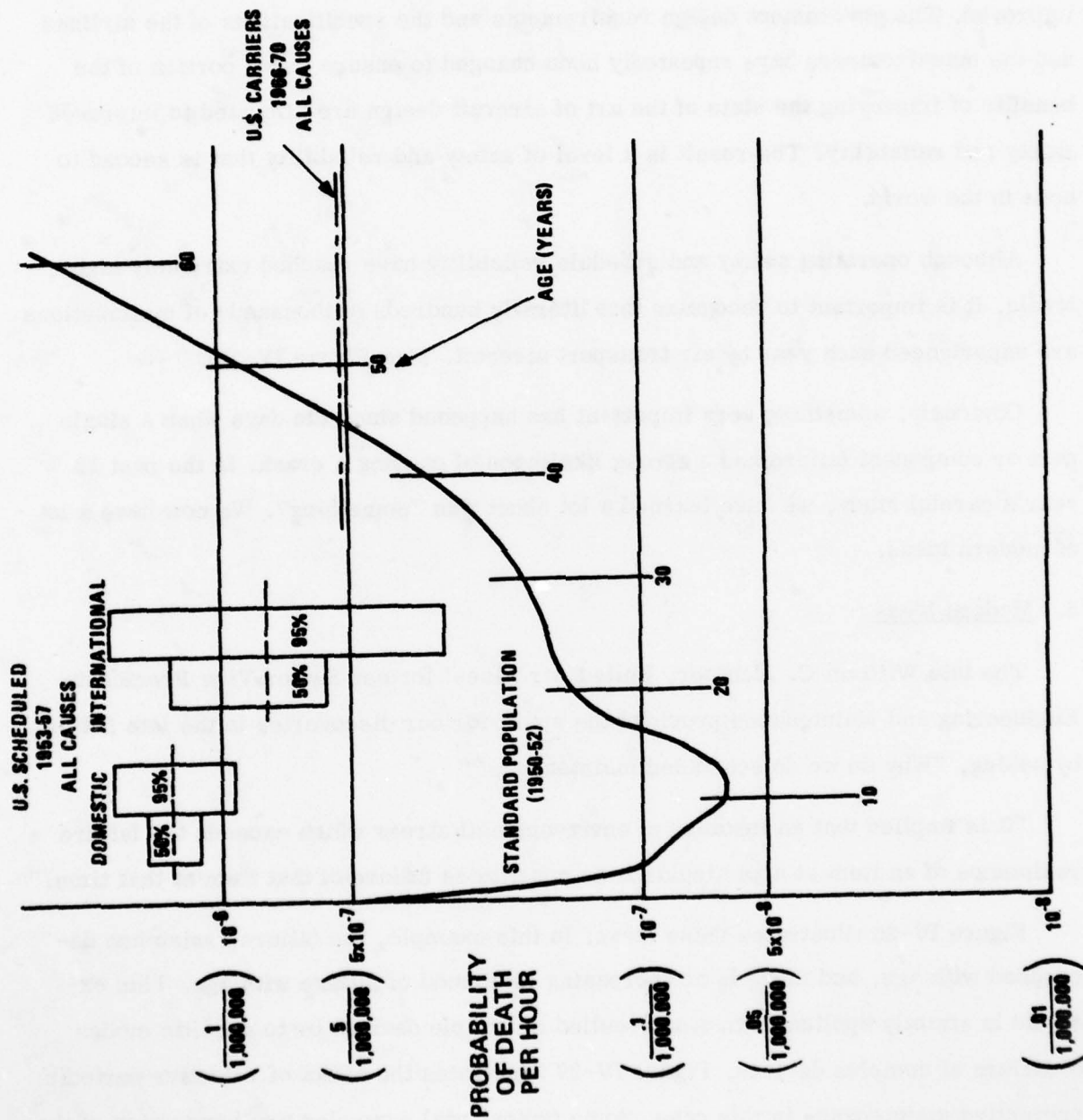


Figure IV-25. Mortality Risk - All Causes vs Air Transport

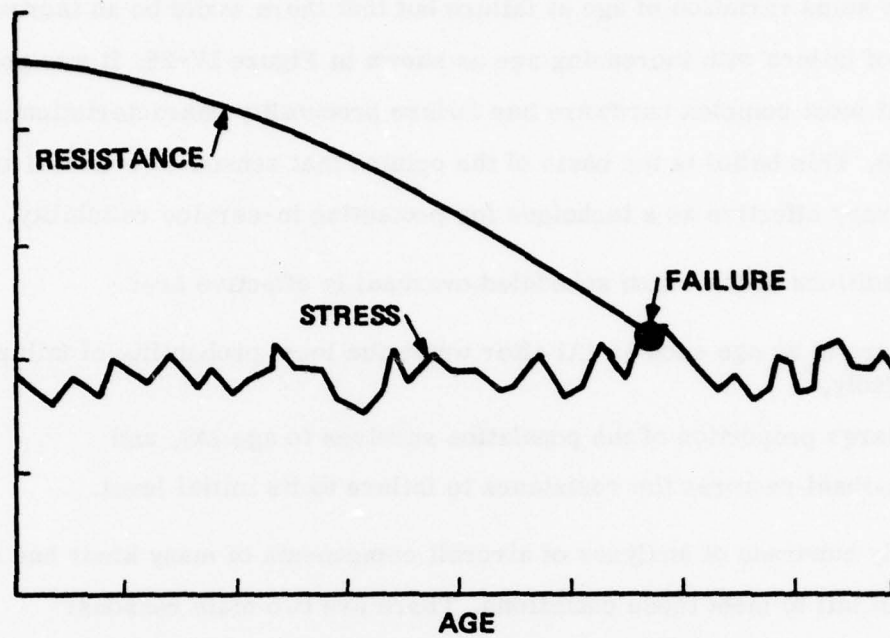


Figure IV-26. Model of Failure Mechanism

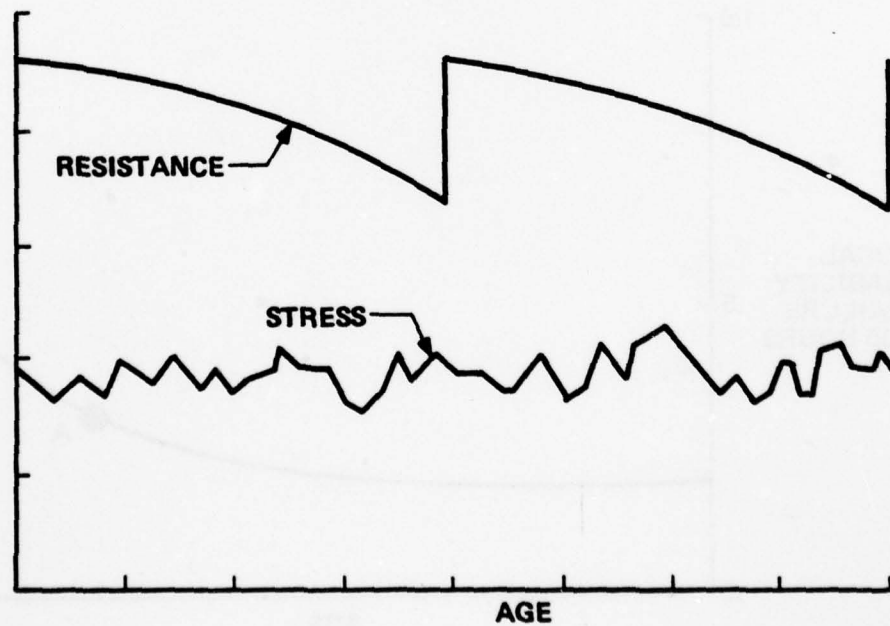


Figure IV-27. Result of Effective Periodic Maintenance

If we extend this reasoning to complex assemblies we would expect that they would demonstrate some variation of age at failure but that there would be an increasing probability of failure with increasing age as shown in Figure IV-28. It was popularly believed that most complex hardware has failure probability characteristics similar to this example. This belief is the basis of the opinion that scheduled overhaul at the right age will be very effective as a technique for protecting in-service reliability.

The conditions under which scheduled overhaul is effective are:

- a) There is an age such as (A) after which the local probability of failure increases rapidly,
- b) A large proportion of the population survives to age (A), and
- c) Overhaul restores the resistance to failure to its initial level.

Literally hundreds of analyses of aircraft components of many kinds has shown that most of them fail to meet these conditions. There are two main reasons:

- There is a wide range of values for failure resistance and environmental stress from part to part in complex assemblies as well as a wide range of



Figure IV-28. Local Probability of Failure

failure modes. Unless these are unusually weak single-celled parts having a dominant failure mode, there is no adverse relationship between age and reliability for the assembly as a whole. The "packaging" of modern hardware of all kinds results in such complexity that in all but a few cases no adverse relationship exists.

- The probability of failure of many units even at relatively low ages is not insignificant, particularly if infant mortality exists. Therefore, even if age (A) exists, so few units survive to that age that the real impact of the failure of the remaining units on the overall failure rate is inconsequential.

Having exposed the general ineffectiveness of scheduled overhauls as a means for ensuring reliability, we might conclude that we should approach the problem of effective maintenance program design by establishing a system for mass analysis of the age-reliability characteristics of all units on an airplane and from the results:

- Assign overhaul times as indicated.
- Allow all other units to operate until failure.

Before deciding on the course of action, some review of the nature of maintenance program is advisable. A maintenance program consists of a group of *scheduled tasks* to be accomplished at specified intervals and a group of *nonscheduled tasks* which results from either the scheduled tasks or from reports of malfunctions, most often by the flight crew.

An efficient program is one which schedules only those tasks necessary to achieve the stated objectives. The determination of these tasks requires a very large number of decisions. It would be nice if a neat input-output model could be developed in which some sets of maintenance programs decisions were the input and the resulting total cost were the output, but this is far beyond our capability. Nevertheless, the use of decision diagrams as a means of logical analysis to select the required scheduled tasks has been proven to be very effective. This approach is based upon a very simple conceptual model which can be summarized as follows:

- a. The purposes of preventive maintenance are to prevent deterioration of the inherent design levels of safety and to improve operating economics.
- b. Safety can be affected either by certain failures of essential systems or by the unavailability of certain standby or back-up systems when required.

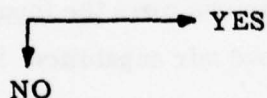
- c. Only maintenance that is effective in preventing failures of systems of the first kind (essential systems) and ensuring the availability of systems of the second kind (standby systems) can have any direct effect on operating safety.
- d. Reduction in the failure resistance of other systems or a decrease in their reliability with age affects economics, not safety, therefore preventive maintenance programs intended to avoid failures of such systems must satisfy the user's cost effectiveness standards rather than safety standards.
- e. Those systems whose failures do not affect safety and whose failures cannot be reduced by some cost-effective preventive maintenance task require no preventive maintenance.
- f. An ex post facto information system is required for use in determining any unanticipated needs for scheduled maintenance or needs for design improvement. This system must include both event-oriented and statistic-oriented sub-systems.

We have seen that age-reliability relationships and the influence of failures on operating safety and economics are the principal elements to be considered in maintenance program design. Now let's apply these ideas.

6. Applying These Ideas

I have first discussed the effect of age on reliability and second, the effect of failures on safety. The order in which these ideas have been introduced is perhaps the easiest way in which to present them. But their application is more efficient if they are reversed. The following questions form the structure of a basic decision tree that considers the influence of failures on operating safety.

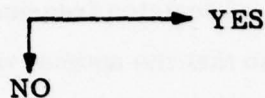
1. Is there a "condition after failure" that has a direct, adverse effect on operating safety?



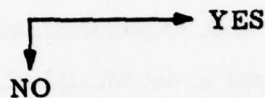
2. Is there a function hidden from the flight crew that has a potential direct adverse effect on operating safety?



3. Is a reduction in resistance to failure detectable by in situ maintenance or unit test ?



4. Is there a demonstrated adverse relationship between age and reliability ?



No scheduled task required.

Question 1 must be asked for each "condition after failure". If the answer to question 1 is YES, either a highly effective maintenance task or redesign is required. If the answer to this question is NO, we proceed to question 2.

Question 2 must be asked for each hidden (dormant) function. If the answer to this question is YES, a maintenance task that tests the availability of this function is required. If the answer to this question is NO, we proceed to question 3.

Question 3 must be asked for each function. If the answer is YES, there is a maintenance task that can measure a reduction in failure resistance. If the answer to this question is NO, we proceed to question 4.

Question 4 must be asked for each function. If the answer is YES, there is a time limit that will be effective in avoiding failures based upon a demonstrated adverse relationship between age and relation such as could be shown by actuarial analysis. If the answer to this question is NO, there are no potentially effective maintenance tasks for the unit or system being considered.

In the interests of obtaining a program that avoids scheduling unnecessary tasks, tasks of doubtful effectiveness that speak to questions 3 or 4 can be omitted and added later, if experience indicates their desirability.

This rather cursory description of a decision tree process for selecting preventive maintenance tasks, you will find, leaves a lot of unanswered questions; e.g. : how do

you apply them to an engine? --- to structures? MSG-2, a publication available from the Air Transport Association, is suggested as a useful reference. You will find in MSG-2 that one of the basic elements of decision tree analysis, the use of an ordered set of questions which act as filters so that the number of units or systems decrease as one progresses down the tree, was discarded in favor of asking all questions of all units. This alternative was chosen by the users to make the process more redundant and decrease the risk of omitting any task requirements. A task requirement can be missed if each function and failure state is not identified before starting.

We can, of course, represent the meaning of this decision tree by the simple matrix shown in Figure IV-29. Now what does this matrix say? It says simply that preventive maintenance can be effective in ensuring safety only when 2 independent conditions exist:

- a. There is a malfunction that affects safety.
- b. There is a preventive maintenance task that works.

	PREV. MAINT. CAN INCREASE \bar{R}	PREV. MAINT. CANNOT INCREASE \bar{R}
MALFUNCTION CAN AFFECT SAFETY	ENSURES SAFETY	REQUIRES DESIGN CHANGE
MALFUNCTION CANNOT AFFECT SAFETY	IMPROVES ECONOMICS	NO VALUE

Figure IV-29. Preventive Maintenance Matrix

It also identifies the condition that mandates redesign, the condition in which economics, not safety can be affected, and last (but not least) the condition in which preventive maintenance is valueless.

Now let's review some of the results of the process I have described.

7. Some Important Results

Perhaps the most important result of this work is that, although it is neither an easy process nor a neat input-output model, we now have a logical process for designing safe, effective maintenance programs for transport airplanes - even though they may not yet have been flown. Before, we were hardly better than fortune tellers. Some insight of the value of this process can be seen from the fact that while the initial maintenance program for the DC-8 specified time-limited overhauls for about 300 units, the initial programs for the 747 and DC-10 specified less than 10. The in-service reliability of the 747, the first airplane having its maintenance program determined by the decision tree process I have described is powerful evidence of the validity of this innovative technique.

Second, we have eliminated the requirement for time-limited overhaul for jet engines. The decision tree logic has clearly identified the limited number of parts in jet engines that require hard time limits and emphasizes the value of On Condition maintenance, using such techniques as borescope and radioisotopic inspections as a means for avoiding operational failures.

Third, we have identified an exhaustive, mutually exclusive set of Primary Maintenance Processes: Time Control (overhaul or discard), On Condition (periodic comparison with condition standards) and Condition Monitoring (the after-the-fact maintenance process which allows operational failures to occur and collects the resultant information to guide future actions). These processes have no self-implied order of importance. Each has its place in an effective maintenance program. The right process for any unit of system is, of course, determined by its design, not by any historical precedence or by intuition.

I hope that these ideas have challenged your thinking as they did mine. I would be surprised if you agreed with all of them instantly. I do hope that you will give them serious thought. Mark Twain, the American 19th Century author once said,

"A round man cannot be expected to fit in a square hole right away.
He must have time to modify his shape."

Many "round men" have modified their shape in the past 12 years and I would like to feel that you all are feeling a little squarer already.

8. References

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MSG-2; Airline/Manufacturer Maintenance Program Planning Document; Air Transport Association of America; March 25, 1970.

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Air Transport Association Facts and Figures; 1970.

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U.S.A. Federal Aviation Regulations and Advisory Circulars.

CHAPTER V

TECHNICAL PAPERS PRESENTED AT THE EVENING SESSION

- A. "AMERICAN SOCIETY OF MECHANICAL ENGINEERS(ASME) WEAR-CONTROL HANDBOOK"
BY W. WINER, GEORGIA INSTITUTE OF TECHNOLOGY

1. Objective

The objective of this proposed ASME Program is to develop a Wear Control Handbook. The contents of the Wear Control Handbook will be in a form which will be readily usable by design engineers, and will contain specific information on the subject of wear to the limits of present technology.

Valuable information on wear phenomena and wear control techniques exists in the technical literature and in the experience of many technical persons. However, it is not readily available to the general engineering community. The objective of the Wear Control Handbook is to make that information available in a useful form.

2. Summary

The Wear Control Handbook Advisory Board of the ASME Research Committee on Lubrication (RCL) is soliciting funds from industry and government to prepare a Wear Control Handbook for engineering design. This program will gather and publish that information which can be used to improve mechanical equipment reliability through wear control. The program will consist of a thorough literature search in the field of wear, selection of design techniques, and preparation of information consistent with the selected techniques.

The Wear Control Handbook will directly benefit you and your Company through:

a. Provision of a Collected Source

At the present time no compilation of usable wear information exists in the literature. Interested design engineers must conduct their own literature search and analyze the heterogeneous data.

b. Better Utilization of Existing Technology

Many new approaches to wear reduction have been developed in the last ten years. These could be exploited by industry but seldom are. The Wear Control Handbook will describe these approaches and their utilization.

c. Conservation of Materials and Energy

Steps are being taken by government and industry to ensure conservation of materials and energy. The best method of materials conservation is to extend equipment life. A great deal of energy is expended in equipment manufacture. Therefore, the extension of equipment life results in direct conservation of materials and energy.

d. Cost Savings to Manufacturers and Consumers

The direct savings to manufacturers resulting from the utilization of a collected source of wear control information is obvious. The indirect but larger savings would be in more reliable designs which would reduce subsequent trouble shooting and retrofitting. Consumers will save billions of dollars each year through reduced maintenance, extended parts life, and improved equipment reliability.

e. More Reliable Design Techniques

Most designs are now based on past experience or by trial and error. The purpose of the Wear Control Handbook will be to present past experience in a form suitable for design and to present techniques which will allow reasonable estimations to be made of service wear where past experience is not available.

3. Description of Proposed Wear Control Handbook

The proposed Wear Control Handbook is divided into two sections: Part I contains a description of general wear phenomena and data; Part II contains information on wear in specific mechanical equipment components (See Table V-1).

The Research Committee on Lubrication has selected Mr. Marshall B. Peterson as Editor. The names of those already contacted to prepare chapters are listed. Authors of the remaining chapters will be selected at a later date.

TABLE V-1. PROPOSED WEAR CONTROL HANDBOOK

Contents

Marshall B. Peterson, Editor

Part I - General Information

Contributors

- | | |
|--|----------------|
| 1. Wear Theory and Mechanisms | E. Rabinowicz |
| 2. Wear Prediction and Design Techniques | M. B. Peterson |
| 3. Load Capacity | J. F. Archard |
| 4. Wear Coefficients, Metals | E. Rabinowicz |
| 5. Wear Coefficients, Non-Metals | K. C. Ludema |
| 6. Lubricated Wear | C. N. Rowe |
| 7. Surface Treatments | D. Guy |

Part II - Component Wear Control

- | | |
|--------------------------------------|----------|
| 8. Bushings | Authors |
| 9. Rings and Cylinders | to |
| 10. Rolling Element Bearings | be |
| 11. Seals | Selected |
| 12. Gears, Splines, and Couplings | |
| 13. Brakes and Clutches | |
| 14. Brushes and Electrical Contacts | |
| 15. Hydraulic System Components | |
| 16. Agriculture and Mining Equipment | |
| 17. Forming Tools and Dies | |
| 18. Cutting Tools | |

The chapter on "Wear Theory and Mechanisms" is intended to be introductory. It will describe the various ways in which wear can occur and the effect of variables on the different types of wear. The chapter entitled "Wear Prediction and Design Technique" will be written by the Handbook editor, M. B. Peterson. In this chapter, he will review the various analytical treatments proposed for service wear prediction and

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PROCEEDINGS OF A WORKSHOP ON WEAR CONTROL TO ACHIEVE PRODUCT DU--ETC(U)
FEB 76 · M J DEVINE

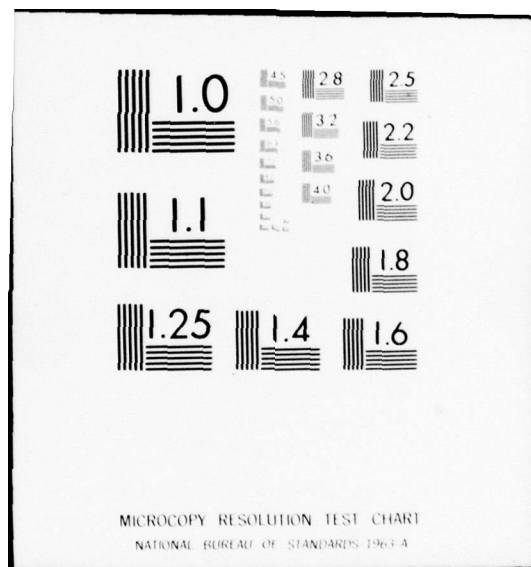
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select the most applicable. This chapter (which will be prepared first) will serve as a guide for the remaining chapters.

The chapters on "Load Capacity" and "Wear Coefficients" will present the generalized design data needed for service wear prediction. These data will be obtained from the literature and presented in the form required for the wear prediction and design techniques selected in Chapter 2.

Chapter 6 will present the case of "Lubricated Wear". This chapter will discuss load capacity and wear coefficients for lubricated conditions, additives for wear prevention and types of wear in lubricated mechanisms. It will discuss the importance of "run-in" to form wear preventing boundary films and design methods for minimizing wear by increasing fluid-film lubrication.

Chapter 7 on "Surface Treatment" will summarize the many different surface treatments for wear control. It will include discussion of the treatments, the metals they can be applied to, the properties of the resulting surfaces, dimensional changes, relative costs, and their effectiveness.

Part II, "Component Wear Control", will contain several chapters which will each summarize the wear knowledge on a particular component. Where possible, selected design techniques will be presented for the particular components.

The quality of the information available and to be presented in these chapters on component wear may vary greatly. On the one extreme is accurate, quantitative information and, on the other, semi-quantitative data which, although not specific, is still valuable to the designer.

4. Program Management

a. Management

The program will be administered contractually by ASME and technically by the Wear Control Handbook Advisory Board of the ASME Research Committee on Lubrication (RCL).

It is fitting that such a project be undertaken by the ASME Research Committee on Lubrication. The Research Committee on Lubrication is the oldest standing research committee of ASME; it will celebrate its 60th anniversary in November 1976. The functions of the committee are as follows:

- (1) To propose, promote, obtain support for and coordinate ASME-sponsored research on lubrication.
- (2) To interpret and disseminate the results of research in this field for practical application.

The Research Committee on Lubrication has successfully undertaken several major jointly sponsored research programs, two of them in the recent past. These include the well known pressure viscosity program (1) completed in 1953 and the critical review of the world literature on boundary lubrication which was published by ASME in 1969. (2) This latter publication contained abstracts of the literature as well as twelve chapters assessing the status of knowledge in particular fields of boundary lubrication. The abstracts were of significant value to experts as a ready source of information, while the chapters summarized information for those with little background in this field. The results of these two programs are history and were well received by the engineering community.

More recently (1970), the Research Committee on Lubrication undertook a research program, now complete, on the chemical effects in contact fatigue. This was a three-year program of research performed by IIT Research Institute under contract to the ASME and its Research Committee on Lubrication. The results of this program were presented in a special symposium at the ASME-ASLE Lubrication Conference in Miami, October 1975.

The above programs were sponsored by industry and government and managed by the ASME Research Committee on Lubrication. The same type of sponsorship, funding and management are planned for the Wear Control Handbook program. The experience gained in the previous programs will be applied to the present one.

The Wear Control Handbook Advisory Board of RCL will have full responsibility for the program. The Executive Committee of the Board consists of the Chairman (Dr. D. F. Wilcock) and two others (Dr. R.S. Fein and Dr. W. O. Winer). The Executive Committee shall be responsible for the day-to-day operation of the program. Decisions pertaining to selections of authors, chapters, or allocation of funds shall be referred to the Advisory Board for approval. The RCL as a whole will periodically review and approve the decisions and actions of the Advisory Board, and when the occasion demands, will be asked by the Advisory Board for approval. The authority for the preparation of the Wear Control Handbook will be vested with the Executive Committee. The editor will work under their direction. The Executive Committee will be responsible for the technical approach and will work closely with the editor in the preparation of the handbook.

The editor and the authors will be contracted through their normal business establishments. They will be selected by the Executive Committee and approved by the Advisory Board.

b. Program Approach

In order to prepare the Wear Control Handbook, a two part program is proposed as follows:

- (1) Part I: In this first phase of the program, the editor will conduct a literature search for titles in the wear field. Excellent sources for this are available from the government. For example, the Defense Documentation Center, NASA, and the Air Force. A foreign abstracting service will also be included which covers the German and Russian literature. This abstracting will be supplemented with the editor's review of the major abstract services: Engineering Index, Chemical Abstracts, Review of the Metal Literature, and American Petroleum Institute Abstracts. Following the literature search, the preparation of the six basic chapters comprising Part I of the Wear Control Handbook will be initiated. The preparation of these chapters will be supervised by the editor to ensure that the collected data are applicable to design. Progress will be monitored and approved by the Advisory Board.
- (2) Part II: After completion of Part I, authors will be selected by the editor and approved by the Advisory Board and chapters prepared on component wear. The selection of chapters will depend to some degree on the information available from the literature and industrial sources.

c. Personnel

As mentioned, the management of the program will be by the Wear Control Handbook Advisory Board of the ASME Research Committee on Lubrication. That Board is listed in Table V-2. The Wear Control Handbook Advisory Board members have had many years of experience, both research and applied, in the field of wear and related disciplines.

The editor of the Wear Control Handbook, Marshall B. Peterson, is a long recognized authority in the field of wear and wear control. Authors of several major chapters have tentatively been selected as listed in Table V-1. These people have indicated a willingness to participate in the program.

Authors for the remaining chapters will be selected during the program. They will be selected by the Advisory Board in consultation with the editor, and approved by RCL.

The editor and the authors selected thus far are recognized as the leading experts in the field of wear. All are now engaged in research and industrial consulting in this field. It is expected that those authors to be chosen will be of comparable stature in the fields they are selected to write about.

d. Schedule

Begin Part I	1 April 1976
Begin Part II	1 April 1977
Complete Part I	1 July 1977
Complete Part II	30 December 1977
Publish Handbook	30 December 1978

5. Program Finance

a. Budget

The estimated costs for this program are shown in Table V-3. These costs are based upon estimates of the hours required when contracted through the authors' normal business channels. All contracting and contract administration will be the responsibility of ASME headquarters staff.

TABLE V-2. WEAR CONTROL HANDBOOK

Advisory Board

Dr. D. F. Wilcock, Chairman
Manager, Tribology Center
Mechanical Technology Incorporated
968 Albany-Shaker Road
Latham, New York 12110
(518) 785-2328

Professor W. O. Winer, Chairman-Finance Subcommittee
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3270

Mr. W. J. Anderson
Head, Bearings Branch
21000 Brookpark Road
Cleveland, Ohio 44135
(216) 433-4000, X468

Mr. M. J. Devine
ARP/SLP Program Office
Naval Air Development Center
Johnsville, Warminster, Pa. 18974
(215) 441-2436

Dr. R. S. Fein
Texaco Research Center
P. O. Box 509
Beacon, New York 12508
(914) 831-3400

Professor E. E. Klaus
Department of Chemical Engineering
Pennsylvania State University
University Park, Pa. 16802
(814) 865-2574

Dr. P. M. Ku
Vice President
Southwest Research Institute
8500 Culebra Road
San Antonio, Texas 78284
(512) 684-5111, X-2375

Mr. A. J. Lemanski
The Boeing Center, M.S. P32-09
P. O. Box 16858
Philadelphia, Pennsylvania

Dr. W. E. Littman
The Timken Company
1835 Dueber Avenue, S. W.
Canton, Ohio 44706
(216) 453-4511, X-305

Professor B. G. Rightmire
Mechanical Engineering Department
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617) 253-2249

Professor A. Seireg
Mechanical Engineering Department
University of Wisconsin
1513 University Avenue
Madison, Wisconsin 53706
(608) 262-3543

Dr. R. L. Adamszak
Wright-Patterson AFB
Research & Technology Division
AFML (MANL)
Dayton, Ohio 45433
(513) 255-3494

TABLE V-3. ESTIMATED COSTS

Literature Search (Titles and References)	\$ 12,000
Chapter Preparation	
Part I, Chapters 1-7	79,000
Part II, Chapters 8-18	132,000
Editing and Administrative Costs	18,000
	<hr/> \$241,000
ASME Overhead	24,000
	<hr/> \$265,000

b. Source of Funds and Contributions in Kind

Because of the significance of a Wear Control Handbook to the entire technical community, it is appropriate that the program to develop it be undertaken by a technical society such as ASME and be funded on as broad a base as possible. For this reason, financial support is sought from both industry and government.

Contributions of \$5,000 or more are solicited. It is expected that contributors will be repaid many times over by the value to their operations provided by information in the Wear Control Handbook.

All contributors will be appropriately listed in the Wear Control Handbook. All contributors will receive a copy of each chapter manuscript when it is approved by the editor and the Advisory Board. During conduct of the project, the ASME Research Committee on Lubrication will have periodic progress review meetings to which contributors will be invited to send a representative. Upon completion of the publication of the Wear Control Handbook, all contributors will receive a complimentary copy.

It is expected that the publication of the Wear Control Handbook will take one year after completion of the manuscripts. Therefore, contributors will have the contents of the book available to them at least one year before it is on sale to the rest of the community.

The Wear Control Handbook will be published by ASME, who will have sole responsibility for its publication and sale, with all resulting income to be applied to the general funds of the Society.

Work on the project will be initiated as soon as sufficient funds are committed to ensure the completion of Part I. Work on the chapters in Part II will be initiated when the remaining required funds are committed.

All contributions should be made payable to The American Society of Mechanical Engineers, designated for the RCL Wear Control Handbook project, and sent to ASME, as follows: ASME Research Department, 345 East 47th Street, New York, N.Y. 10017. Copies of the Wear Control Handbook Proposal (3) are available from the same address.

Persons interested in further details about the proposed project should contact either the Advisory Board chairman, Dr. D. F. Wilcock, or the chairman of the subcommittee on finance, Professor W. O. Winer, at their respective addresses below:

Dr. Donald F. Wilcock
Mechanical Technology, Inc.
968 Albany-Shaker Road
Latham, New York 12110
(518) 785-2328

Professor Ward O. Winer
School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
(404) 894-3270

6. References

- (1) Pressure Viscosity Report - Published by ASME 1954.
 - (2) Boundary Lubrication - An Appraisal of World Literature, F. F. Ling, E. E. Klaus and R. S. Fein, editors, American Society of Mechanical Engineers, New York, 1969.
 - (3) Wear Control Handbook Proposal (1975) copies available upon request from the Research Department, ASME, 345 47th Street, New York, N.Y. 10017.
- B. "THE AMERICAN SOCIETY OF LUBRICATION ENGINEERS 1976: ESTIMATE OF THE ANNUAL REPLACEMENT COST FOR WEAR AND FAILURE OF TRIBOLOGICAL MECHANICAL COMPONENTS AND MATERIALS IN THE UNITED STATES" BY R. L. JOHNSON, RENSSELAER POLYTECHNIC INSTITUTE

The American Society of Lubrication Engineers has sustained interest in documenting the cost of wear and failure of tribological materials and mechanical components in the United States. The data are for use in achieving recognition and support for our

interdisciplinary technology and in guiding the course of the activities for ASLE. In this, we are referring to the Technical Committee activity in particular. Other technical societies such as ASTM, ASME, and the Federated Materials Society, have related interest in activities. It is clear, however, that the available information is inadequate on which to justify a continuing acceleration of studies and technology development in the area of lubrication science.

In the structure of ASLE, there is an Organization and Operations Committee, which reports to the President of the Society. It serves in an advisory or consultant capacity, on special problems that usually have long term significance. Also, the Committee considers problem areas on its own initiative that it thinks may have future impact on the organization and the operation of the Society. Again, reporting to the Board of the Society through the National President. Typical results of the deliberations of the Committee, guide actions taken by the Board of Directors for example, in the modification of the Technical Committee and the Industrial Council Organization within the Society and also, in the status of the administrative committee structure in the Society.

The present consideration in the O & O Committee on cost of wear replacement in the United States is pointed toward documenting the economic significance of lubrication, friction and wear (tribology). Demonstrating economic impact is one approach to gaining industrial and governmental support for expanding activities critical to our Society and which are essential to reduce present waste of materials and energy for our nation.

The original consideration of our Committee was to attempt to achieve a broad estimate of the total significance of tribology technology to the economics of the industrial community in the United States, that is, the total cost of wear and friction. The members of our Committee, who incidentally, are generally former officials of the Society, considered many ways of doing this from the standpoint of how the sampling methods can proceed and how the results of this can be made statistically significant. We indulged in some activities to determine if replacement costs as indicated by warranty records in companies, could be used for this purpose. In personal discussions, our members sampled some of the largest corporations in the United States that produce automotive and industrial machines to see what types of records are available.

In addition, insurance companies were contacted in regard to failure records. One of our committee members had been involved with some military studies of maintenance practices and we explored the different sources of information to see what approach could be taken to generate a total statistic that would be meaningful. We decided that to establish the cost of replacement of worn parts would be a significant undertaking, but one that was amenable to the type of operation that we were forced to pursue.

Our Committee had no funding, only the limited support that each of us had was from our respective employing organizations. The ASLE Headquarters staff can handle the mail handling but are not equipped for survey activities. Thus, very little could be done in the way of direct personal interviews with those people who had the kind of information desired. Thereafter, the plan was developed for achieving statistics on replacement wear which seems to offer some promise for giving significant data. In this, we chose to develop a coordinated listing of types of industrial concerns; it encompasses that of the Department of Commerce and that used by Fortune magazine. So accordingly, we developed a listing of categories to be surveyed which included about 50 different categories. In each category we selected a trade association or some other organization which we thought could estimate the total problem of wear for that particular industry. Also, we selected one or two, preferably two, industrial concerns who we knew were interested in this area: in many cases, they were Industrial Members of ASLE. While it was not always possible to do so, we have chosen to address the highest level of technical management in the company, one having the authority to request someone in his company to develop the needed information if they wish to cooperate. The survey is being made by letter, and is in process now. A transmittal letter is sent over the signature of Mr. Harry Tankus, who is the National President of the American Society of Lubrication Engineers, along with a survey questionnaire which asks the following ten questions:

1. Please estimate the annual replacement cost for wear and failure, not obsolescence, of mechanical components and materials.
2. Estimate the percentages of the cost attributed to the five major cost replacement tribological components, that is bearings, gears, or seals, etc.

3. To estimate the relative importance of the types of wear problems. That is to identify the most troublesome types of wear such as adhesive wear, abrasive wear, corrosive wear, etc.
4. The manufacturers of mechanical components only are asked to indicate the five largest industrial replacement markets for their product.
5. Asks about the design philosophy of the company or organization whether they were concerned with early failures, design margin, or the normal life.
6. Inquires as to what kinds of wear is most troublesome in what kind of component, that is the process type and component type. (e. g. dirt abrasion of gear).
7. Seeks to learn if there are professional specialists on lubrication friction and wear of mechanical components, in the research and development design or maintenance staffs of your organization. And if not, what is your source of help on these types of problems. Whether, for example, from suppliers, or from consultants or engineering institutes, etc.
8. Asks the respondent if they may be listed as an information source.
9. Seeks to learn if details of the response may be known in reporting.
10. (The final question) provides for the responder to express viewpoints:
 - a. to clarify or expand on the responses;
 - b. to indicate what breakthroughs in tribological sciences are anticipated, and indicating special problem areas where breakthroughs are urgently needed;
 - c. to comment with regard to federal policies needed to encourage this technology;
 - d. a request for general comments on relevant matters as the respondent wishes.

Now, as to the present status of this survey. We are in the process of sending out the questionnaires, they have been sent to associations that represent these different categories. The specific addressees for the second group will be individuals in companies. We would welcome your suggestions for potential sources of information. In many categories there will be at least one, but in a number of cases 2, or 3 companies will be contacted. Historically the response from questionnaires of this type is very often in the range of 15 to 30%, and so to get the distribution of respondents that is needed, it may be necessary to send follow-up questionnaires to other sources or to make individual contacts within the company's name.

As yet, no responses to the questionnaires mailed have been tabulated. They are being received and tabulated by the National Headquarters of the American Society of Lubrication Engineers. They will be analyzed first by the O & O Committee, and secondly, the cooperation of the National Science Foundation Coordinated Tribology Program at RPI, Georgia Tech and Northwestern is anticipated for assistance in statistically analyzing the results obtained.

This presentation in itself, should suggest to you that the results from the ASLE Program and that being pursued by the Congressional Office of Technical Assessment, will be coordinated. The type of information being sought by the OTA is somewhat greater scope than simple replacement cost. You are in the process of gaining insights as to the OTA plans which are concerned with specific types of materials. The types of material involved did not determine the selection of categories for surveying in the ASLE Program. Rather, the ASLE Program attempts to get a more restrictive type of information, that is, replacement wear only from a complete spectrum of the industrial community in the United States.

In concluding this discussion, I want to emphasize that the approach taken by the ASLE Organization and Operations Committee in trying to establish replacement costs for wear, is the approach that we felt could achieve the most results with the least cost to the Society, and the individuals concerned. There is no question that if there were funding available for survey interviews to bring out all the facets of the problems and to document the problems of gaining responses in themselves, more meaningful data could be developed. That, however, would be a program beyond the resources available to our ASLE Committee. All the information achieved in our ASLE activities will be made available to all concerned with due respect for the wishes of the respondents. In particular, the Congressional Office of Technology Assessment will be fully informed.

C. "AMERICAN SOCIETY OF TESTING AND MATERIALS COMMITTEE G-2 ON
EROSION AND WEAR"
BY K. C. LUDEMA, UNIVERSITY OF MICHIGAN

Activities in wear in Committee G-2 had its beginning when the technical community itself began to feel the need to standardize wear terminology and wear test methods.

An Ad Hoc Committee on Wear was formed and it met in ASTM headquarters. After the first meeting in 1970, ASTM was asked to approve the formation of a regular committee on Wear. ASTM advised the group to contact the existing Committee G-2 on Cavitation Erosion to see if that Committee would broaden its scope to include the subject of Wear as it is ordinarily defined. The Ad Hoc group agreed to do so on March 10, 1971, and addressed a request to the officers of G-2 in May 1971. By December 1971, the scope of G-2 was changed, the Committee was renamed and the Ad Hoc group became a formal sub-committee of G-2. With the addition of the wear activity, the membership doubled to about 75 members.

The first meetings of the wear sub-committee were devoted to identifying those areas in which standards could be written. A questionnaire sent to 270 names elicited an overwhelming response, identifying 35 products, components and materials as needing wear standards of some form. The range of topics was very broad, covering such diverse topics as:

- Seals and Packings
- Hard facing
- Wear of Carbon
- Wear of mining, agriculture and construction equipment, etc.

Several of the 35 topics were pursued by interested individuals and publicity was given to them with the hope of attracting others. For a time, interest seemed high in about 10 of the topics. Action began on fretting, the wear of tool steels and the wear of polymer extrusion dies. However, people in those fields had already made professional commitments to other societies and were not in a position to divide their loyalties, particularly in the ever-tightening budget situation in which industry has bound itself in the last five years. On the other hand, certain mature fields such as the wear testing of hard-facing metals progressed well, and progress is reported at each meeting. Recently, interest has also developed in writing standards for wear of components in business machines such as typewriters, computer print-out devices, etc.

Early in the discussions on wear standards it became apparent that whereas a great many people are interested in the activity of Committee G-2, much discussion and communication was devoted to defining terms, and sorting out mechanisms of wear. It is never possible to determine whether the diverse terminology used by those concerned with the subject of wear arises from different meanings for the same words, or different perception of the same mechanism of wear. We, therefore, planned a tutorial session on wear, wherein five papers were read which were aimed at summarizing the mechanisms of wear and aiding the group in arriving at common terminology and descriptions of wear. That session was held in Boston on May 22, 1974, with 75 in attendance. The next such activity was held in New Orleans on November 20, 1975. This meeting attracted 75 also but an almost completely different group than the Boston meeting. The papers of the two sessions are to be published as a standard technical publication of ASTM.

The next conference activity in which Committee G-2 will participate is the International Conference on the Wear of Materials - 1977, to be held in St. Louis together with ASME, ASLE, SME, ASM, and SAE. This conference is an effort to attract scientists and engineers from various industries, such as the textile industry, heavy equipment industry, and many more to meet together. It is often found that the wear community is divided up into several camps. Those wear problems which appear to be alleviated by lubrication are attacked by lubricant chemists and bearing designers, some of whom are also involved in elastohydrodynamic analysis. On the other hand, the wear of ball mills, bulldozer tracks, razor blades and railroad wheels are found in the metallurgical societies. Automotive related topics are covered in the SAE, tool wear is the domain of SME and textile wear is explored in several textile-industry based societies. There is as much common interest as there is diversity among all of these professional groups, however, and that common interest will be developed in the Conference. In our memory, no such grand and overall conference has ever been attempted. In fact, the scope of that conference will be broader than that of the workshop we are here attending. Erosion is not to be ignored at the International Conference.

In that conference, erosion is a sub-division of wear. Already a session is planned on erosive wear of concrete such as highway surfaces, the surfaces of public buildings, and rock drilling.

Committee G-2 plans to continue programs of standardization. In particular, we consider it our proper domain to sponsor forums on terminology, methods of wear testing, methods of reporting wear test results, and on standardizing the method of expressing the wear life of components available to the designer. For the latter activity, we consider it vital to involve designers as well as suppliers of materials and components. This implies publicizing our goals among people who are not now aware of our existence, or who have not been motivated to join a voluntary consensus standardization activity such as ASTM is.

D. "THE MECHANICAL FAILURES PREVENTION GROUP INTEREST IN WEAR"
BY E. E. KLAUS, PROFESSOR OF CHEMICAL ENGINEERING, THE PENNSYLVANIA
STATE UNIVERSITY

The Mechanical Failures Prevention Group (MFPG) was organized in 1967 under the sponsorship of the Office of Naval Research to focus on mechanical failure technology. Reliability, safety and improved economics are among the obvious goals for a better understanding of mechanical failures. The original objectives of MFPG listed in Figure V-1 are the basis of the four working committees.

MFPG is an interdisciplinary group with a strong applications orientation. The constituency of MFPG as indicated in Figure V-2 includes professional personnel representing a wide variety of scientific and engineering disciplines. The individual scientists and engineers come from Government Agencies, Universities, Research Institutes and Industry. They represent an interest in the activities of the MFPG. Cooperation with appropriate committees or units of professional societies is also involved.

The MFPG administrative organization is shown in Figure V-3. This figure represents the original ONR organizational structure. The committee structure was modified slightly in 1971 when the sponsored role was shifted from ONR to the National

**ORGANIZED 1967
SPONSOR - ONR**

OBJECTIVES

- 1. UNDERSTAND FAILURE MECHANISMS**
- 2. DESIGN TO PREVENT FAILURE**
- 3. DETECT, DIAGNOSE, AND PREDICT
INCIPIENT FAILURE**
- 4. STATE OF THE ART TECHNOLOGY**

**Figure V-1. Mechanical Failures Prevention Group
MFPG**

GOVERNMENT AGENCIES

EDUCATIONAL INSTITUTIONS

RESEARCH INSTITUTES

BUSINESS COMMUNITY

**PROFESSIONAL SOCIETIES
(INDIRECT COOPERATION)**

Figure V-2. Constituency of MFPG

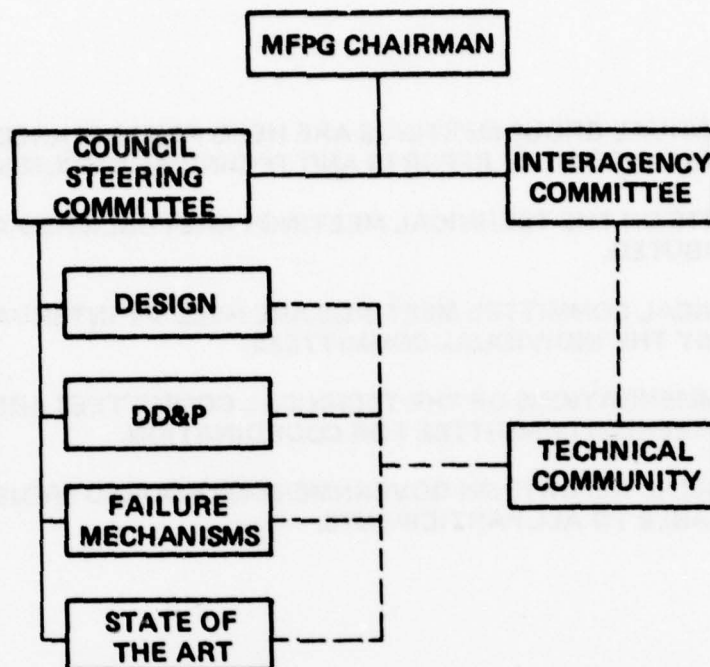


Figure V-3. MFPG Administrative Organization

Bureau of Standards. Under this revised structure, the steering committee became the council. The chairman, vice chairman, executive secretary, and the chairmen of the interagency committee and the four technical committees make up the council.

The communications among the constituency of MFPG are shown in Figure V-4. The technical committees are responsible for the semi-annual group meetings. These meetings include technical talks, informal program reports, and technical panel discussions that emphasize current work in progress. Emphasis at these meetings is on a meaningful discussion on the technical presentations. The written record of the meetings includes a preprint version including short (one page or less) abstracts of all of the presentations. A proceedings is published for each meeting which contains a long abstract (typically 5-7 pages) of each presentation and the meaningful discussion following the presentation. These proceedings are published and distributed to the attendees at the meeting. Proceedings as long as the supply lasts is available on request.

SEMIANNUAL GROUP MEETINGS ARE HELD FOR PREPARED TALKS, INFORMAL PROGRAM REPORTS AND TECHNICAL DISCUSSIONS.

REPORTS ON THE TECHNICAL MEETINGS ARE PUBLISHED AND DISTRIBUTED.

TECHNICAL COMMITTEE MEETINGS ARE HELD AT INTERVALS DECIDED UPON BY THE INDIVIDUAL COMMITTEES.

RECOMMENDATIONS OF THE TECHNICAL COMMITTEES ARE FORWARDED TO A STEERING COMMITTEE FOR COORDINATION.

TECHNICAL REPORTS ON GOVERNMENT-SPONSORED PROJECTS ARE AVAILABLE TO ALL PARTICIPANTS.

Figure V-4. Communication Among MFPG Participants

Technical committee meetings are held in conjunction with technical meetings as well as special meetings as required. The action of the technical committees are coordinated by the council. The activities of the committees and council are announced periodically through an MFPG Newsletter published on the basis of available information.

A number of technical reports on government sponsored projects spawned by MFPG meeting activities are made available to all interested participants.

The four technical committees of MFPG are responsible for the technical meeting programs. The meetings were held quarterly and programmed by all four committees for the first five symposia. As the group attending these quarterly meetings began to exceed 200 per meeting and the program became more general and diverse, the meetings were changed to single theme meetings sponsored by a single technical committee.

These single theme meetings started in 1968, were continued on a quarterly basis until late in 1971. From 1972 to the present time, meetings are held semi-annually.

The technical purposes of the meetings sponsored by MFPG, as shown in Figure V-5, are to provide a truly interdisciplinary communications system. These meetings have been designed to focus on failure problems from a technological viewpoint. Subjects with practical applications were examined from many technological positions. The clear focus on a technical problem determines the extent of interest and overlap or redundancy in research in a given area. This type of scrutiny also determines some holes in the technology that need but are not receiving attention. The MFPG and committees of MFPG are available to provide a consultative roll to the government or private sector in many technological areas.

A look at the meeting themes for the mechanisms and state of the art committees will illustrate how these technical purposes were implemented. These two committees lend themselves to themes that are easily identified with an applied technology. The

**PROVIDE AN INTERDISCIPLINARY COMMUNICATIONS
SYSTEM**

**FOCUS ON IMPORTANT TECHNOLOGICAL PROBLEMS
INVOLVING FAILURE**

**DETERMINE EXTENT OF INTEREST, OVERLAP, AND
"HOLES" IN SPECIFIC TECHNOLOGY**

**PROVIDE CONSULTATIVE ROLE FOR GOVERNMENT AND
PRIVATE SECTOR ON SPECIFIC TECHNOLOGICAL
PROBLEMS**

Figure V-5. Technical Purposes of MFPG

design and the diagnosis, detection, and prognosis committees covered a series of equally interesting topics that are harder to recognize from the meeting titles. The meetings sponsored by the mechanisms of failure committee are listed in Figure V-6. The applied nature as well as the interdisciplinary character of these subjects is obvious at a glance.

The focus on mechanisms of failure as applied to helicopter transmissions was done in cooperation with several groups in the Department of Defense. The mechanical fatigue mechanisms meeting was programmed as a broad brush look at the similarities and differences between the mechanistic views of bending and contact fatigue. This meeting was sponsored cooperatively with the Research Committee on lubrication of ASME as general background interest for a program on the chemical effect of contact fatigue. The meeting on cavitation is a typical example of the advantage of MFPG over a technical society. In this meeting, the expertise in cavitation mechanisms developed in the systems involving water was explored in detail. On the other hand, attempts were made to look

- 1. HELICOPTER TRANSMISSION FAILURE**
- 2. MECHANICAL FATIGUE AS A CRITICAL FAILURE MECHANISM**
- 3. CORROSION EFFECTS IN MECHANICAL FAILURE**
- 4. THE ROLE OF CAVITATION IN MECHANICAL FAILURE**
- 5. THE ROLE OF COATINGS IN THE PREVENTION OF MECHANICAL FAILURE**

Figure V-6. Mechanisms Committee Meetings

critically at cavitation in nonaqueous hydraulic and lubrication systems. In these latter areas, the problems are in many cases not as severe or well defined. This type of cross fertilization proved to be effective.

The State of the Art Committee meetings are shown in Figure V-7. Again the applied aspects of the subjects are easy to recognize. The failures in aircraft engines were evaluated and compared for commercial as well as military service. The meeting on the identification of failure modes and their detection in internal combustion engine systems covered a wide range of approaches. This meeting pointed up the growing technology of detection devices mounted in operational engines to detect incipient failure or significant engine malfunction. This subject provided the basis for the first MFPG effort in contract research.

The meeting designed to evaluate critically the use of lube oil analysis in mechanical failure detection examined three basic approaches. The spectrographic oil analysis program (SOAP) was compared with more comprehensive oil analyses. These basically oil oriented analyses were then compared with the analysis of wear debris by both physical and chemical methods.

The most recent meeting of the State of the Art Committee on "Definition of the Problem" was designed to articulate the size, economic, technological, and social consequences of mechanical failure. In addition, the applications of tribology, a new technology encompassing many aspects of lubrication and other mechanical failures, were investigated in a series of presentations. The objectives of this MFPG meeting resembles the general focal point of the present effort of the Office of Technology assessment in the assessment of wear.

In the operation of MFPG, the cooperation of all the groups listed in Figure V-2 has been excellent. The group of federal agencies participating is shown in Figure V-8.

- 1. CRITICAL FAILURE PROBLEM AREAS IN AIRCRAFT
TURBINE ENGINES**
- 2. IDENTIFICATION AND PREVENTION OF FAILURES IN
INTERNAL COMBUSTION ENGINE SYSTEMS**
- 3. MECHANICAL FAILURE PREVENTION BY LUBE OIL
ANALYSIS**
- 4. DEFINITION OF THE PROBLEM**

Figure V-7. State of the Art Committee

Support from the education, research and industrial sectors has been excellent. The enthusiasm for this type of interdisciplinary group capable of focusing on items of current applications interest remains high.

The MFPG has recently demonstrated another capability. NAVSEC requested that MFPG review the feasibility of condition monitoring for the prevention of mechanical failure. This request was answered by a committee of MFPG with representation from all the technical committees. The actual project was carried out by MFPG with a subcontract to Marshall Peterson of Wear Science Inc. The work was carried out by a group of four investigators including expertise in diesel engines, diagnosis, transducers, and tribology. The focus was on the possibilities of effective condition monitoring of the three diesel engines in a class 1179 Navy ship. The actual work was guided by a committee of MFPG. The program has now been completed with several recommendations suggesting that condition monitoring of the diesel engines on such a

DEPARTMENT OF TRANSPORTATION
U.S. COAST GUARD
FEDERAL HIGHWAYS ADMINISTRATION
FEDERAL AVIATION ADMINISTRATION
DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
MARITIME COMMISSIONS
ATOMIC ENERGY COMMISSION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
DEPARTMENT OF DEFENSE
ADVANCED RESEARCH PROJECTS AGENCY
INSTITUTE FOR DEFENSE ANALYSIS
U.S. ARMY
U.S. NAVY
U.S. MARINE CORPS
U.S. AIR FORCE

Figure V-8. Participating Federal Agencies

ship would be cost effective. The report also identifies improvements in technology that would be effective in improving current technological capability in this area. The most important result of this feasibility study was the demonstration that an interdisciplinary group of volunteers could pool their expertise effectively to accomplish a project that would be difficult to approach from a single discipline.

CHAPTER VI

CONTRIBUTED TECHNICAL PAPERS

A. "CONSERVATION TECHNIQUES AS PRACTICED IN POWER TOOL MANUFACTURE" BY MARVIN FEIR, ROCKWELL INTERNATIONAL

A general overview of the materials and energy conservation picture requires that one looks at not only the availability of raw materials, the manufacturing processes and the durability of product, but also at the waste caused by redundancy. Reference in this case is to the duplication or triplication caused by the completion of bad deliveries, materials not processed to standards, and/or the problems caused by lack of communication between suppliers and manufacturers.

Energy and material conservation have become rallying points about which it has become rather the "in" thing to raise the flag in very recent times. There are, however, a number of companies that have always been concerned with waste, if only because it was such a diluent of profits.

The problems of immediate massive conservation cannot be solved by a number of diverse industries or companies making drastic changes on the spur of the moment, no matter how pure and idealistic the intent. There has historically been a reluctance to communicate between various industries, and this in turn has led to a great deal of waste and, in some cases, lawsuits. It seems that few basic supply industries know their customers' needs and the wide ranging effects that a simple decision can have. This same situation applies within individual companies where the supervisor of a department will use a solution to a problem merely to get it out of his lap regardless of how badly it will affect another department down the line. Usually this will cost the company a great deal more in the long run. The point of all this is basically that, for maximum effectiveness, a sound policy of material and energy conservation has to start at the ground level, not somewhere along the fortieth floor. Naturally, the tenants at all levels have to do whatever they can; but, if the stairwells are blocked and the elevators shaky, the results will be less than ideal.

Assuming the basic honesty of people, one can only attribute the types of miscalculation seen to lack of information and hope that avenues of communication can be opened by work shops and seminars where mutual problems can be attacked and their possible solutions derived.

Okay, now to basics -- today's favorite whipping boy, the petroleum and gas industry, makes a logical starting area. There is a general recognition that a shortage of gas exists and the need for peak shaving and other methods of gas extension are a necessity and a fact of life that industry in general will have to live with. For general heat extraction, these processes do not have a major effect; but, for metal-working areas, where carbon potential, dew point, and soot must be controlled to very fine limits, certainly there is a more materials and energy effective way for fabricators of metal goods to be apprised of changes in gas composition than for each of them to buy an automatic gas density determinator so that untold amounts of material will not be reduced to scrap. This area is where a large communications gap exists and really needs to be resolved. Obviously, there is also a shortage of good bottled gas so the buck cannot be passed by the recommendation to change over. Even so, there is the use of steel for tanks and pipes and pumps which could make the conversion more materials costly than tolerable.

It is amazing that the petroleum industry, which has really developed some superb lubricants and has done such a fine job in the overall picture, has allowed itself to be entrapped by some of the simple but ridiculous situations that have proven so costly to others. A few examples of thoughtlessness rather than intentional malfeasance are:

- 1.) The absolute assurance that one mineral oil is the exact substitute for another in all situations, with the disregard that the second oil has some antioxidant additives which makes it completely unsuitable for use in vacuum systems -- waste of time, manpower, energy, oil, work load, perhaps equipment refurbishing.

- 2.) Many plastics these days are rather selective in regard to the chemicals they can tolerate. Grease formulae have been changed many times with no word to consumers, primarily because oil companies have run standard tests and concluded that lubricity has not been affected. This may have been a proper and safe procedure in the past, but now consider the results if a series of hand tools should craze crack and disintegrate in the hands of their users. Open communication of formulae changes would be most appreciated in the avoidance of such incidents.
- 3.) There have also been occasions where proprietary lubricants have been specified and the oil company involved has been asked to provide the consumer with test methods or prove that their product was, in fact, being used. It is inconceivable, but they had no such tests and wanted to charge for the development of these tests.

We are fortunate at Rockwell in that we have complete chemical laboratory facilities because a complaint to oil companies has never been admitted as an error on their part until absolute proof has been submitted.

The adverse effects of changes in oil additives are also wear and longevity factors in powder metal parts, where it has been found that some products cause problems with the leaching out of copper, some cause intergranular or crevice corrosion, some do not maintain proper film strength -- all of which reduce gear life or bearing life well below design parameters.

The preceding paragraphs are meant only to illustrate factors beyond the control of tool manufacturers that affect the life of their products.

Another area of concern is that of raw materials whether cast iron, steel, aluminum, die casting, plastics or zinc.

There seems to be a greater tendency for mills to deliver "out of specification" materials without previous consultation with the consumer. We all know that there are many cases where off-grade or substitute materials will do very nicely; but, when designs are updated to make more efficient use of materials, the manufacturer or designer should have the prerogative of acceptance or refusal of a delivery, not the supplier who is unaware of the properties needed in the final product.

It is not uncommon for off-grade steel to be delivered. It is necessary to check every delivery from warehouses for mixed steel shipments. Fifty percent of the proprietary grades of steel purchased do not meet the producers' published properties. The industry, as always, will replace any defective material, but there is no recuperation from the loss of time, energy, and machine wear that went into the attempt to use the improper shipment. This is a particular hardship on small manufacturers who simply cannot set up complete test facilities for all incoming materials.

Foundries also have caused their share of inconvenience and waste, regardless of whether their product was sand, die, or permanent mold castings. The advent of governmental controls in this industry has only served to exacerbate the situation and is, in fact, a leading cause for many industries to design away from castings to other processes, which are or were once considered too expensive and cost ineffective but are now preferred over castings because of both cost and quality levels. The promulgation of too many unwise regulations too quickly has forced the closing of small foundries and created a situation in which larger ones are unable to accept short run jobs on a profitable economic basis. Too often for comfort, malleable or ductile iron is not. Aluminum die castings, if painted yellow, could be mistaken for Swiss cheese and foundries are restricting the variety of alloys they will cast to even further limit the choice available to consumers.

The comments on foundries are, of course, directly translatable to forging shops.

And, finally, but of major importance to us because of mandated double-insulated requirements, the plastics industry. This industry has seen phenomenal growth in a great variety of products; but, the basic specifications of thermoplastics such as the spread of molecular weight, melt viscosity index, percentage of additives including coloring matter, and the release agents have been determined solely by the basic producers, and there is no assurance that any two deliveries will be the same. This problem is intensified by the fact that very few, if any, custom parts molders have either the equipment or personnel needed to test incoming raw material so that

literally millions of plastics parts per year are molded from non-satisfactory material, which in critical parts calls for rejection, and all the energy, manpower and time used in this manufacture is wasted and three times as much energy is used in return and reshipment of parts. This in addition to the possibility that the manufacturer waiting for these parts may have to shut down an assembly line either because unusable parts have been delivered or because the molder found he made weak parts, after the fact. The end user of plastics parts cannot and should not assume the responsibility of testing raw materials for molders. But very definite restrictions should be imposed on some raw plastics specifications and this can only occur after molders have gotten into the routine of checking incoming raw materials and learning what they can really use for critical parts and what they cannot use. Power tool people are all too familiar with consumer safety problems and have developed good receiving inspection techniques so this aspect is not a major concern here, but we are concerned with material and energy wastage and believe that plastics molders should be made aware of their safety responsibilities in addition to their moral responsibilities to deliver the materials they claim to make.

At Rockwell, there has been a continuing program of materials evaluation and development for a number of years. The present situation has resulted in some intensification of our efforts and in the establishment of better communication channels so that more rapid response can be made to changing situations and conditions.

In 1973, an inventory of all materials in stock was taken. A review of parts then current was undertaken and a materials list was recommended that would reduce both the number of material grades and sizes needed to make parts to a minimum. A program of inventory reduction was then pursued until all extraneous material was consumed and inventory lists brought into line. All prints were then brought up-to-date to reflect these changes.

Due to the realization that spot shortages could and probably would occur, a hot line was established between plant production personnel and the Materials Engineering

Department so that, should alternate material recommendations and approval be necessary, this could be secured without delay, based on the actual properties needed rather than mere chemical similarity.

The routine testing of incoming materials and purchased parts was programmed into all plants. The avoidance of surprises during fabrication and assembly operations and their attendant shutdowns and delays has resulted in savings, both in materials and energy.

For greater ease in description, we can divide materials areas into the following classifications:

- Structural parts
- Gears and bevels
- Shafts
- Bearings
- Electrical
- Materials treatments

Structural parts by our definition are portable tool housings and stationary tool tables, legs and guards.

Among stationary tool materials, gray cast iron has historically been the most widely used for stands, tables, frames, yokes and trunnions. We have found that for one saw model we could replace the cast iron table and stand with stamped sheet metal. In another model, permanent molded aluminum is used. In a band saw application, weldments have replaced cast iron, and sheet metal or plastic used as guards and closures. In drill presses, more plastic guards are used to enclose belt drives. Particle board is used in radial arm saw tables rather than solid lumber.

In the portable hand tools, which were originally designed for polycarbonate housings, extensive stress-strain studies have been in process for some time, and

the result has been a gradual improvement in performance with a decrease in weight that amounts to almost 30% in some tools. The knowledge gained has allowed the use of the highest impact strength material at no more cost per tool than lesser plastics would cost. Further evaluations of plastics and design are in progress to continue the more efficient use of materials in this area. In a few cases, the substitution of plastic for aluminum has resulted in improved impact resistance and reduced warranty costs, in addition to the savings in energy conversion.

Gears and load bearing parts are for the most part being designed in powdered metals. Great success has been achieved in replacing cut or broached gears at no practical loss in tool life. With the energy crunch, further savings are being realized by judicious alloying to eliminate the need to heat treat parts. There has also been a concurrent effort to use leaner alloys wherever possible.

Motor shafts, idler shafts and other parts of this type have traditionally been made from carbon steel or low alloy in areas of greatest stress. Where possible, cold drawing to eliminate heat treatment or the use of leaner alloys has been instituted. Numerous small stamped parts are used and a study program of the possible substitution of H.S. L. A. steels for low carbon sheet has been started and, as in the automotive field, could result in the use of lower tonnages of steel to make equal numbers of tools at no loss in quality.

Many bearings are oil impregnated P/M bronze. Programs are under way to replace the less critical ones with either P/M iron or iron diluted bronze, which would conserve considerable copper and tin. Where roller and ball bearings are used, no replacement is now on the horizon, although the use of plastic cages is being studied as another possible savings of steel and heat treatment facilities.

New automated electric motor assembly lines have been installed which reduce scrap considerably, which has resulted in materials savings. There have also been considerable energy savings realized by the change to automated balancing and testing of these parts.

Where painting is done, systems have been changed to water-based materials at substantial savings in energy and pollution prevention. Black oxidizing and cleaning operations have been and are being converted to low-temperature baths to reduce energy usage. At least one heat treating facility was closed to consolidate energy and protective atmosphere usage. Small plating facilities have been phased out and work sent to commercial houses as a further means of reducing energy usage.

Power tools in all categories are subject to life-cycle tests, which insure relatively accurate prediction of their performance in the hands of ultimate users. While there are no formal industry-wide length of life criteria for each class of tool, Rockwell, for one, will not tolerate tool life that is second to anyone. Among major tool manufacturers, the competitive system has had the very positive result of lower prices for longer-lived tools.

In closing, it seems that there are many interplaying forces at work and, perhaps before a great deal of time and effort is spent on piecemeal apparent savings, a basic philosophical decision should be made as to whether the power tool industry should continue to supply relatively low-cost, shorter-lived tools for virtually everyone or whether only more expensive, longer-lived tools should be manufactured for the professional or semi-pro. Only after this has been determined can general plans of performance be drawn up. At present, there is an overlap of performance between various grades of tools and it is very likely that any sizeable improvement in life and performance of the promotional line of tools will merely result in their effective removal from the marketplace in favor of the next priced line which is already there, or the elimination of the professional lines of tools because of the finite difference in life versus the large difference in price. It is no secret that, at the present time, a number of construction people are using replaceable low-cost tools rather than the more expensive models which were designed with their needs in mind and with a virtual indefinite life.

Perhaps if everyone heeded the words of John Ruskin the path of conservation would be most clearly defined:

"There is hardly anything in the world that some man cannot make a little worse and sell a little cheaper, and the people who consider price only are this man's lawful prey."

B. "ECONOMIC IMPACT OF TECHNOLOGY CHANGES BY COST SIMULATION"*
BY SHAKER RESEARCH CORPORATION

1. Introduction

Cost modeling is a useful technique to aid in the establishment of research directions, implementation priorities, and specification strategies. This discussion provides a brief discussion of a simulation technique for: 1) developing simulation cost models; 2) determining which costs, probabilities, and other parameters for individual components most affect system costs; and 3) determining system costs associated with the individual components.

The simulation approach to cost modeling is different from other commonly used cost modeling techniques. The most common technique, life cycle costing, "follows" a particular component from its original purchase through use to eventual retirement (in a statistical sense). All costs attributable to the component are included in the cost total. This type of model is useful in determining the actual overall cost of a component to the industry which is employing it. However, the life cycle cost model is not very suitable in determining the yearly cost required to use the component. In addition, the data requirements for the life cycle cost model can be difficult to meet.

In the simulation approach, the costs are obtained by "following" the system in its use of the component. A dynamic simulation model of the "flow" of the component of interest throughout the system is developed. The model then computes the cost per year to operate that part of the system related to the component under consideration.

*Excerpt from Phase I Report, prepared under contract DOT/TSC-917

2. Technical Approach

Cost simulation can be a valuable tool in a determination of economic costs. Typically, use of cost simulation in such a determination first requires that a representation be created for the cost system under consideration. Next, parameter values must be provided. This step frequently involves field collection and statistical reduction of data. Finally, the computer is run to obtain costs associated with various parts of the system. Usually, other information about the cost system under consideration is also obtained.

In the simulation procedure, a schematic diagram is first developed to represent the cost sources of interest. The diagram also defines the modeled system, the various interactions to be considered, and the number and type of parameter values to be provided. The operation of the cost system, as given by the schematic diagram, is then programmed for the digital computer. In this, a dynamic modeling technique is used. As a result, the costs and system behavior are obtained not only for a given time but also for any future time of interest.

a. Application Example

This simulation approach has been applied to the determination of costs associated with freight car roller bearings used by the railroad industry. A short description of the roller bearing application is given below as an example of the cost simulation process.

The schematic diagram which was prepared to represent the railroad industry's use of roller bearings is shown in Figure VI-1. This figure portrays the events in the railcar roller bearing's life between the time it is manufactured and the time it is scrapped. For the purpose of the analysis, the railcar bearing was assumed to be in one of four locations within the system:

- (1) In the field either in actual use or sitting on the line, on a siding, or other location where normal maintenance would not take place;
- (2) In a yard where routine bearing inspections and axle removal could take place;

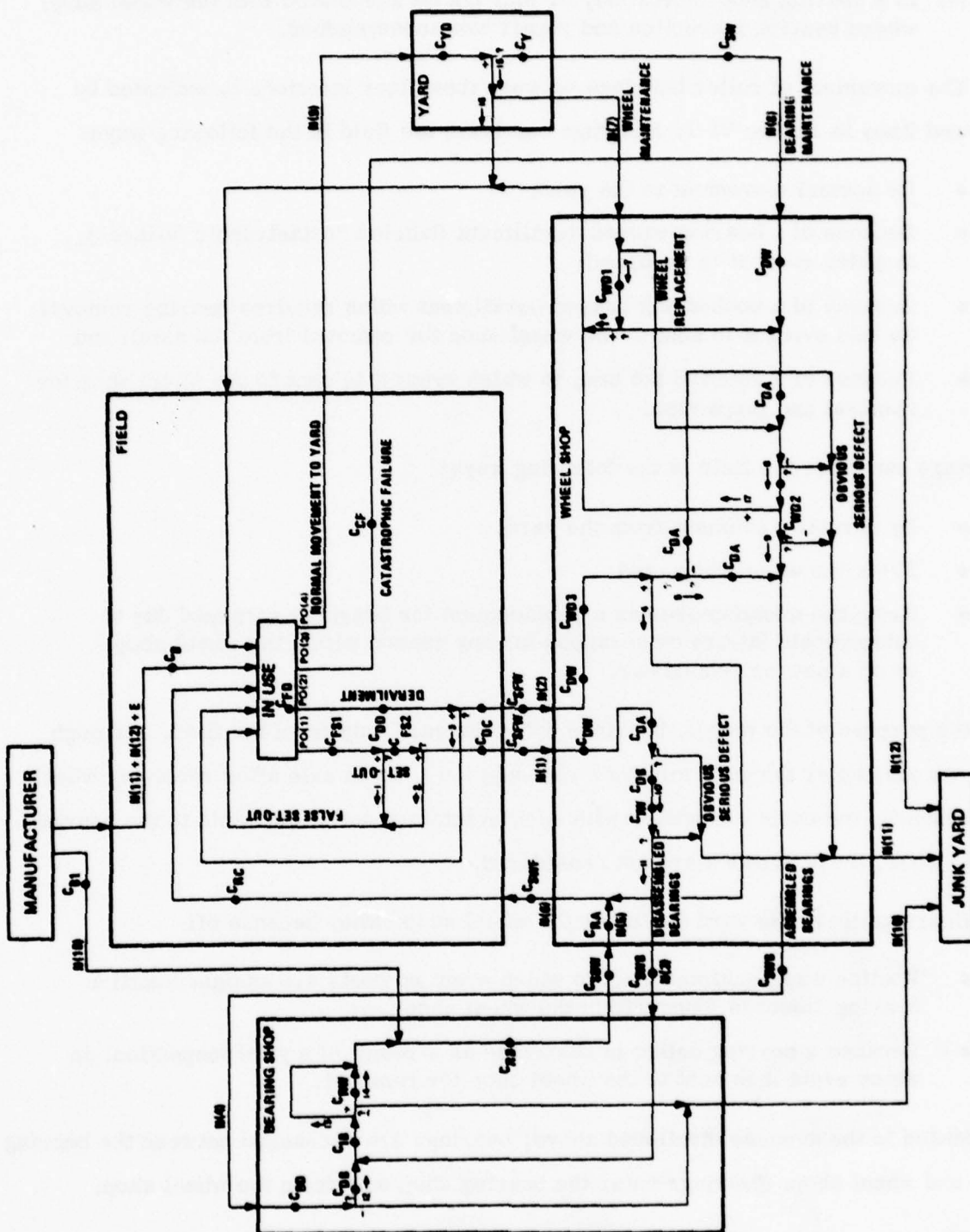


Figure VI-1. Roller Bearing System Cost Schematic

- (3) In a wheel shop where bearing removal and inspection is accomplished; or
- (4) In a bearing shop (which may or may not be associated with the wheel shop) where bearing inspection and repair are accomplished.

The movement of roller bearings between these four locations is indicated by arrowed lines in Figure VI-1. Bearings can leave the field in the following ways:

- By normal movement to the yard;
- Because of a bearing caused derailment (labeled "catastrophic failure"), in which event it is scrapped;
- Because of a nonbearing caused derailment which requires bearing removal (in this event it is sent to the wheel shop for removal from the axle); and
- Because of a verified hot box, in which event it is sent to the wheel shop for removal and inspection.

Bearings can enter the field in the following ways:

- By normal movement from the yard,
- From the wheel shop, and
- From the manufacturer as a replacement for bearings scrapped due to catastrophic failure or scrapped for any reason within the wheel shop; or on a new or rebuilt car.

For the purpose of the model, bearings enter the yard only from the field. Although they can also enter the yard for other reasons; i. e., on an axle after receiving wheel maintenance, the costs associated with such events are not attributable to the bearing itself. Thus, these avenues are not considered.

Bearings leave the yard and enter the wheel shop either because of:

- Routine wheel maintenance (in which event no costs are assigned until a bearing defect is found within the wheel shop), or
- Because a bearing defect is suspected as a result of a yard inspection, in which event it is sent to the wheel shop for removal.

In addition to the avenues mentioned above, bearings are exchanged between the bearing shop and wheel shop. Bearings enter the bearing shop only from the wheel shop.

The paths within each of the four areas are varied and depend upon the condition of the bearing at various locations within each area. Furthermore, all the paths are

not currently allowable. For example, a return path to "in use" within the "field" is shown on the nonbearing caused "derailment" path. This and other paths within the wheel shop and bearing shop were provided in the model to explore the cost-benefit of such alternatives.

The paths shown contain branch points and junction points. Each branch point is numbered and is a decision point; i.e., a point where bearings considered to be good (+), questionable (?), bad (-), or reworkable (S) are separated. The junction points are those points where the bearing paths join. No decision is associated with these junction points.

All arrowheads shown at the branches and junctions indicate from which path(s) the bearings are arriving. Paths leaving from these connection points do not contain arrowheads.

The symbol N is used to denote the total number of bearings in the composite bearing system. The fraction of the N bearings that leave "in use" per year in each of the four paths shown is given by $PO(\quad)$. For example, if $N = 8 \times 10^6$ roller bearings and $PO(3) = 5 \times 10^{-6}$ then $8 \times 10^6 \times 5 \times 10^{-6} = 40$ bearings per year are associated with a catastrophic roller bearing failure.

Many of the paths entering the six elements of the system are labeled $N(\quad)$. Each label indicates the number of roller bearings per year in that path. The symbol E refers to the number of roller bearings per year added to the railroad system for the purpose of expanding the number of roller bearings in the system.

Various costs are associated with the paths taken by the bearings. Each cost is labeled $C(\quad)$ where the cost is in dollars per bearing (with the exception of C_{FD}^*). These individual costs include labor, material, shipping, and/or out-of-service costs associated with each event in the system. Thus, cost associated with any event is the product of the individual cost and the number of bearings involved; the cost of any path is the sum of the event costs within the path; and the total system cost is the sum of all path costs.

*The cost C_{FD} was assumed to be a fixed yearly cost associated with maintaining and operating the hot box detection system.

3. Typical Results

The cost simulation approach can be used to obtain total system and/or branch costs for either a single company or for an entire industry. In the preceding example, it was used on an industry-wide (U. S.) basis.

Some typical results are shown in Figure VI-2. The table insert, for example, shows how total system cost varies with bearing reject rate.

The model can also exercise its time-dependent mode to obtain an estimate of how the average age of the population would change with time and how the bearing shop reject rate would effect the average age.

To accomplish this, the total bearing population, all costs, and all splits (except splits 13 and 14) were held constant; i. e., at the same values used in the base case. Split 14 was set to zero to prohibit bearings to be hand reworked (spall and brinell grinding) in the model. Split 13 was set at 0.8, 0.6, 0.4, and 0.2 (representing a shop reject rate of 20%, 40%, 60%, and 80%, respectively.)

The results of these runs are shown in Figure VI-2 where it is seen that at current reject rates (20%), the average age of the population is increasing at a rapid rate. Information like that shown in Figure VI-2 can be used to estimate the potential future catastrophic failures (bearing-caused derailments).

C. "NEW APPROACHES TO MATERIALS CONSERVATION BASED ON POLYMER COATING TECHNOLOGY"

BY E. ROESER AND D. MINUTI, NAVAL AIR DEVELOPMENT CENTER

A number of powder coating techniques have been explored for application to Naval aircraft and ship equipment. The highly corrosive marine environment has required laboratory tests designed to simulate in-service operating conditions in determining the effectiveness of powder coating compared to conventional surface treatment. The specific areas investigated were: (1) Sonic Fatigue - Airframes; (2) Abrasion - Ground Support Equipment; (3) Erosion - Airfoils and Hydrofoils; (4) Wear Control of Aircraft Components.

The work under this program pioneered processing technology for electrostatic and plasma processing for aerospace and ship applications. New engineering approaches based on plasma were developed and materials/processes are described.

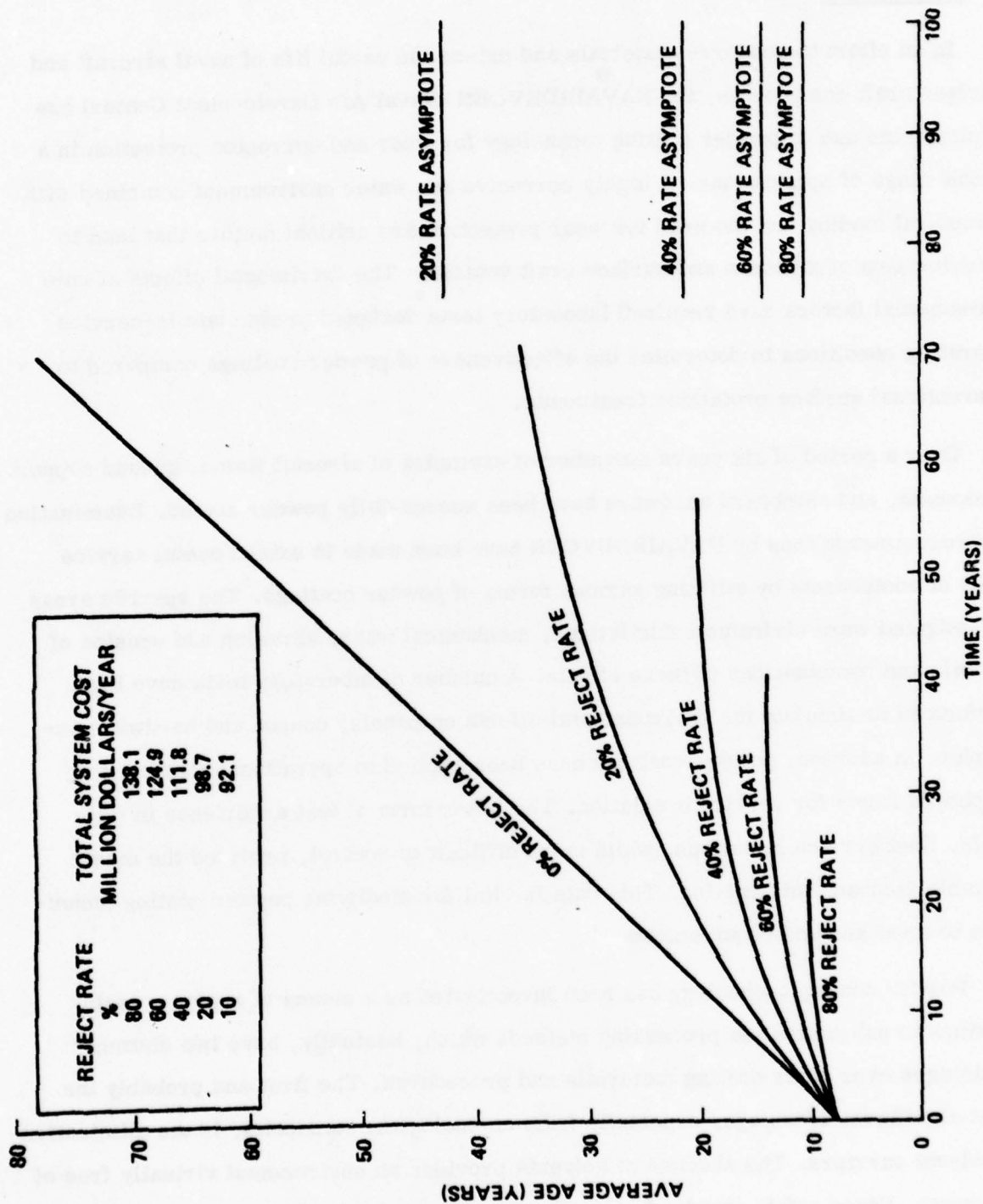


Figure VI-2. Effects of Bearing Shop Reject on Average Age and Total System Cost

1. Introduction

In an effort to conserve materials and extend the useful life of naval aircraft and surface craft components, the NAVAIRDEVCEN (Naval Air Development Center) has explored the use of powder coating technology for wear and corrosion protection in a broad range of applications. A highly corrosive sea water environment combined with structural loading and the need for wear protection are critical factors that lead to deterioration of airborne and surface craft vehicles. The detrimental effects of environmental factors have required laboratory tests designed to simulate in-service operating conditions to determine the effectiveness of powder coatings compared to conventional surface protection treatments.

Over a period of six years a number of examples of aircraft items, ground support equipment, and shipboard hardware have been successfully powder coated. Examination and recommendations by NAVAIRDEVCEN have been made to extend useful service lives of components by utilizing various forms of powder coatings. The specific areas investigated were airframe sonic fatigue, mechanical wear, abrasion and erosion of airfoils and combinations of these effects. A number of laboratory tests have been performed to simulate the environmental effects on panels, coupon and hardware examples. In addition, powder coatings have been applied to operational aircraft and shipboard items for service evaluation. The latter form of test experience in full-scale, fleet service situations, while more difficult to control, provided the most valuable feedback information. This data is vital for modifying powder coating techniques to meet service requirements.

Powder coating technology has been investigated as a means of applying resin coatings to substrates via processing methods which, basically, have two distinct advantages over other coating materials and procedures. The first and probably the most significant advantage, especially from an ecological standpoint, is the elimination of solvent carriers. The absence of solvents provides an environment virtually free of pollutants. Other safety standards are also improved because the hazards of fire are substantially reduced. The second advantage that results from this processing technology

is its ability to form protective resin coating which cannot be applied in any other manner without difficulty, particularly because of the poor solubility of the resins in most solvents. Thus many coating properties can be obtained which were not previously available. Three techniques have evolved from the principles of fluidized bed and the electrostatic spray, including their hybridization. A more recent process uses the thermal energy and velocity of a plasma spray to apply a wide variety of plastic compositions. This latter technique, called the plasma spray process, originated as a method to deposit high melting temperature metals and ceramic materials. Further rationalization of this process has led to the development of the thermal gun applicator.

Below are reported some of the results of current efforts to enlarge the arena of effectiveness for powder coatings whatever the method of application.

2. Metal Fatigue

Fatigue of aircraft components, including propulsion drive system parts, such as spline connections, is a major cause of aircraft downtime. Coatings on metal parts subjected to repeated loads have been shown to have increased fatigue life over uncoated parts.

To test for beneficial effects, the Tatnall-Krouse constant speed flexure fatigue apparatus (Fig. VI-3) was used to study the fatigue properties of plastic coated steel and titanium alloy specimens. The machine was designed primarily for the testing of sheet material under all ranges of stress. The loading force of an electric motor is transmitted directly to a variable throw crank. The specimen is fatigue tested as a simple cantilever beam.

The configuration of the standard test specimen used in this apparatus is shown in Figure VI-4. For steel test specimens (AISI 1010) the thickness of the sheet was 0.035 inches, while for the titanium alloy (Ti-6Al-4V) a thickness of 0.076 inches was used.

Three powder coating materials were deposited on the AISI 1010 steel; nylon 11, vinyl, and epoxy. Since nylon and vinyl require a primer, fatigue tests were performed

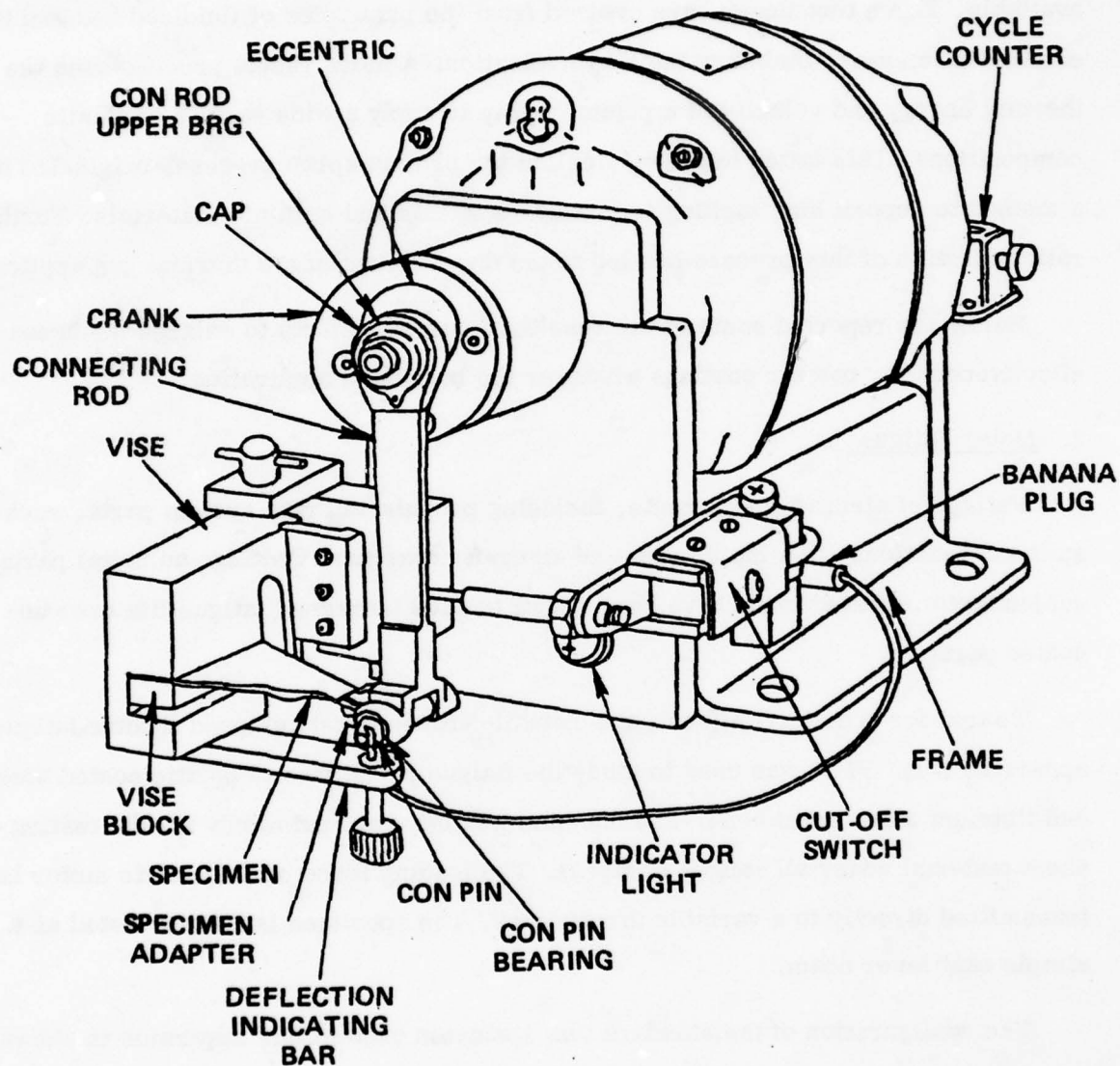


Figure VI-3. Tatnall-Krouse Constant Speed Flexure Fatigue Apparatus

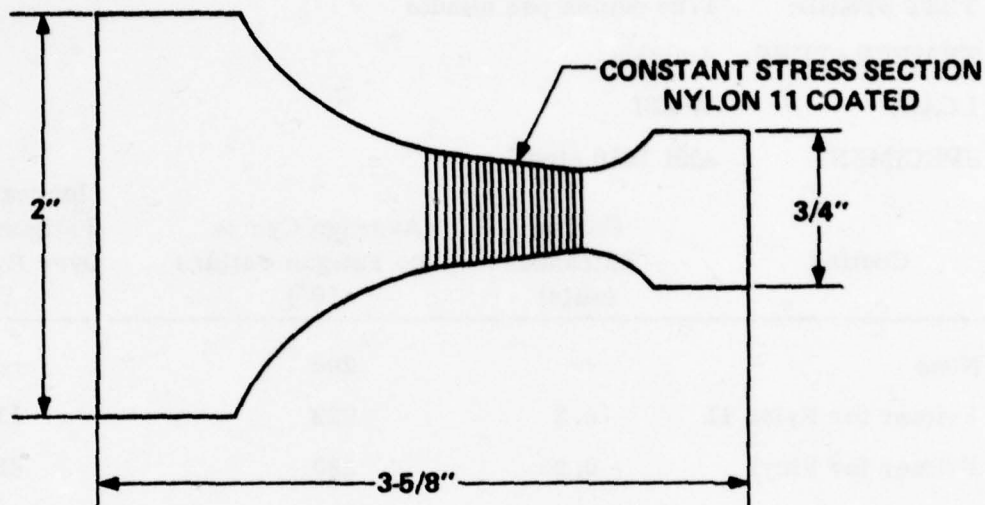


Figure VI-4. Configuration of the Standard Test Specimen

to determine the effect of the primer material. Table VI-1 shows the average number of cycles (6 tests each) to failure for the various steel specimens studied. It can be observed that powder coatings of vinyl, nylon 11, and epoxy are effective in increasing resistance to flexure fatigue failure, the relative order of fatigue resistance being epoxy nylon 11 vinyl. A similar increase in fatigue life was also observed for nylon 11 coated Ti-6Al-4V alloy specimens, Table VI-2.

The reasons for increased fatigue life are that the coating provides a protective layer of material which acts as a shield against atmospheric moisture and other contaminants. Fatigue tests of bare metal run in a vacuum, for example, show three to four times as much fatigue life as the same specimen run in a typical test laboratory environment. Acoustical fatigue of structural elements represents an extensive repair/replacement requirement for military aircraft. Techniques to solve such fatigue problems include increasing stiffness by adding stiffeners or increasing skin thickness. Unfortunately,

TABLE VI-1. FATIGUE LIFE TEST RESULTS FOR STEEL

APPARATUS: Tatnall-Krouse constant speed flexure fatigue
 TEST SPEED: 1725 cycles per minute
 TEMPERATURE: Ambient
 LOAD: 40 KSI
 SPECIMEN: AISI 1010 steel

Coating	Coating Thickness (Mils)	Average Cycles To Fatigue Failure (10^3)	Increase In Fatigue Life Over Baseline %
None	--	200	--
Primer for Nylon 11	0.2	222	11
Primer for Vinyl	0.2	290	45
Nylon 11 + Primer	7	496	148
Vinyl + Primer	7	380	90
Epoxy	7	642	220
Alkyd Paint	--	305	53

TABLE VI-2. FATIGUE LIFE TEST RESULTS FOR TITANIUM ALLOY

APPARATUS: Tatnall-Krouse constant speed flexure fatigue
 TEST SPEED: 1725 cycles per minute
 TEMPERATURE: Ambient
 LOAD: 80 KSI
 SPECIMEN: Ti-5Al-4V

	Coating Thickness (Mils)	Average Cycles To Failure (10^3)	Increase In Fatigue Life Over Baseline %
None	--	75	--
Primer for Nylon 11	0.2	115	53
Nylon 11 + Primer	7.0	1000*	--

*Indicates test discontinued; no failure observed

structural weight is also increased. An alternate solution to this problem is based on the application of polymer coating materials to provide sonic damping. A specimen consisting of a section removed from the rear fuselage of an A-6 aircraft was fatigue tested in a high intensity noise environment. The test consisted of four phases. Phase I established suitable locations for the installation of strain gages. Phase 2 produced strain data from the bare uncoated fuselage and Phase 3 established strain values for the coated fuselage. Phase 4 determined the integrity of the coatings during a 50-hour high-intensity sonic fatigue test. Four coatings were selected for the test. Two were polysulfides, one using a lead, the other using a zinc catalyst; the third was a polyurethane and the fourth a nylon plasma spray coating. The results of the test show that (1) the external coatings did not reduce the strains in the panels, (2) coating integrity was maintained during the 50-hour high-intensity sonic fatigue test, (3) and areas having no damping coating showed evidence of crack formation and crack growth. It was also observed that crack formation did not occur with nylon 11 coating.

Also, experimental coating materials were applied to sections of A-6 aircraft fuselages, see Fig. VI-5. Two sections of A-6 aircraft fuselage cut from stricken aircraft, and flat test panel sections typical of aircraft skin-stringer were made. Radiographic inspection of operational A-6 aircraft fuselage areas made during the study showed that damping coatings inhibited crack growth. After 146 flight hours of operations a crack 0.5 inches long was found. Another inspection was made after 232 additional flight hours. Two additional cracks were visible through the paint system and three by X-ray examination. The uncoated control aircraft after 248 flight hours of operations showed 27 fatigue cracks in a number of structural members. Also, it was noted that structural repairs of cracked skins in two areas had been made. The A-6 fuselage sections coated with elastomeric polyurethane, polysulfide and nylon 11 were examined before and after laboratory sonic fatigue testing showed that crack growth was essentially eliminated by the damping coatings, but those panels having no damping coatings exhibited significant crack growth. This observed difference was attributed to the damping action of the plastic film on the sonic vibration occurring in the substrate structure. Hence, based on these preliminary findings, the advantages

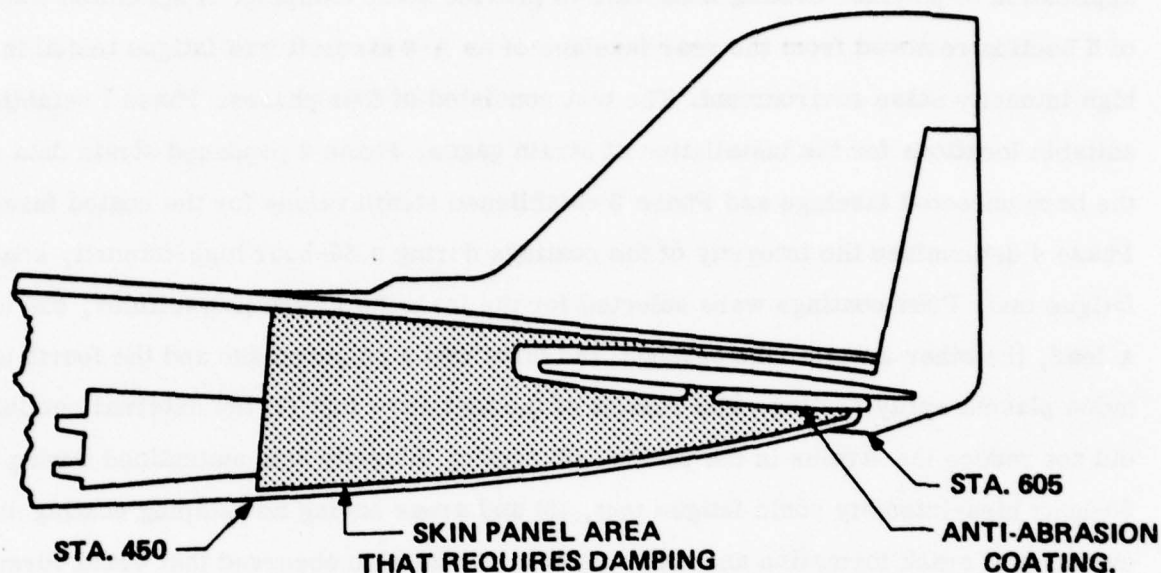


Figure VI-5. A-6 Aircraft Fuselage from Station 450 to 605

in using damping coatings on A-6 aircraft fuselage areas are to reduce crack formation and crack growth. It is recommended that continued efforts be made to exploit this technology for other aircraft having sonic fatigue problems. It may prove useful for noise reduction in submarine and ship applications.

3. Abrasion/Erosion

The ability of a coating to withstand erosion by dust, rain, etc. is an important requisite of aircraft coatings. However, certain areas such as leading edges and radomes require high abrasion resistant coating because these areas are subjected to high velocity impact during flight. For this purpose, elastomeric coatings such as neoprene, hypalon, and elastomeric polyurethane are presently used in many aircraft applications. These materials have exhibited superior abrasion resistance properties over nonelastomeric coatings.

Of the non-elastomeric coatings a polyurethane was found to give the best abrasion resistant properties for general aircraft use. Because of the inability to form insoluble resin coatings by conventional paint spraying, materials such as nylon have not previously been evaluated for abrasion resistance. Since powder coating technology has provided a means by which such coating can be applied to substrates, it was of interest to investigate the abrasion protection of nylon 11.

The S.S. White Industrial "Airbrasive" Unit K was used to obtain performance data on the abrasion resistance of various coatings. This apparatus performs a controlled cutting action by the impingement of sharp-edged particles of calcium magnesium carbonate under regulated air pressure on a sample undergoing test.

The apparatus consists essentially of a vibrator, mixing chamber and nozzle, plus solenoids and valves necessary to regulate air pressure and flow of the dolomite. The mixing chamber is mounted on the vibrator, which in turn is activated by a flow of current and shakes the mixing chamber at a constant rate depending on the voltage. The higher the voltage, the more vigorous the vibration of the mixing chamber and the faster the flow of abrasive. Air under regulated pressure flows into the mixing chamber and forces the abrasive particles through the nozzle on to the specimen under test.

The various coatings investigated were applied to 3" X 6" X 0.031" AISI 4130 steel panels. These test specimens were affixed to the test apparatus and eroded by the abrasive until a small round portion of the substrate appeared. The total time in seconds required to abrade through a given thickness of coating was recorded.

Table VI-3 shows the results of the abrasion tests on elastomeric paints, non-elastomeric paints and a nylon 11 powder coating. The last column which is designated "normalized time" represents the average time required to abrade one mil of coating. This figure was obtained by dividing the time required to abrade the coating by the coating thickness. The greater the normalized time the more abrasion resistant the coating. As is indicated in the table, the elastomeric paints are indeed much more abrasion-resistant than the non-elastomeric paints. Of the non-elastomeric paints investigated, a polyurethane exhibits abrasion resistance properties which are

TABLE VI-3. ABRASION TEST RESULTS ON ELASTOMERIC/NON-ELASTOMERIC
PAINTS AND NYLON 11 POWDER COATING

APPARATUS: S.S. White Industrial "Airbrasive" Unit K
 ABRASIVE: 50 u Dolomite
 NOZZLE TIP TO
 SAMPLE DISTANCE: 0.625"
 ABRASIVE FLOW RATE: 25 grams per minute
 SPRAY PRESSURE: 40 PSI
 SUBSTRATE: AISI 4130 Steel

Coating	Thickness (Mils)	Time Required to Abrade Coating (Sec)	Normalized Time (Sec/Mils)
Neoprene	4.9	160	33
	2.7	95	35
Hypalon	5.1	95	19
	4.1	80	20
Polyurethane (Elastomeric)	10	600	60
Polyurethane	12	117	9.8
Epoxy Paint	4	6.0	1.5
Vinyl Paint	3.0	5.0	1.7
	5.1	15	2.9
Nylon 11	3.6	259	72

superior to neoprene and hypalon and is somewhat greater than elastomeric polyurethane. This data also shows that powder coatings of nylon 11 are of potential importance for use on aircraft leading edge and radome applications.

An interesting effect on abrasion resistance was observed for nylon 11 coated test specimens which were quenched in water immediately after being taken from the oven. Table VI-4 shows the results of abrasion tests on quenched and unquenched nylon 11 coated test specimens at 60 psi spray pressure. A significant decrease in abrasion resistance was noted for the quenched coating. It is considered that these

TABLE VI-4. ABRASION TEST RESULTS FOR NYLON 11 COATING

APPARATUS: S.S. White Industrial "Airbrasive" Unit K
 ABRASIVE: 50 u Dolomite
 NOZZLE TIP TO
 SAMPLE DISTANCE: 0.625"
 ABRASIVE FLOW
 RATE: 25 grams per minute
 SPRAY PRESSURE: 60 PSI
 SUBSTRATE: AISI 4130 Steel

Coating	Thickness (Mils)	Time Required to Abrade Coating (Sec)	Normalized Time (Sec/Mils)
Nylon 11 (cooled at room temperature)	4.0	89	22
Nylon 11 (Quenched in water)	4.0	89	14

findings are a result of the amount of crystallinity associated with the nylon 11 coating. A quenched coating will have a greater amount of amorphous structure.

A very interesting application was provided by the opportunity to powder coat mine sweeping sled hydrofoils, as shown in Figure VI-6. These "wings" which are designed to lift and fly through water have proved to be very difficult to protect. Normally applied paint systems rapidly lose their effectiveness during operations due primarily to the abrasion/erosion by sea water after which corrosion effects are observed. In connection with preliminary studies for this application, the data of Table VI-5 were obtained. The Water Vapor Transmission Rate (WVTR) is done according to Method 3030 of Federal Test Method Standard No. 101. To obtain the films for this test, the coatings were sprayed onto a teflon sheet. They were dried for seven days at room temperature and then removed from the teflon backing in a single sheet for WVTR testing. Results presented in the table for the plasma applied nylon 11 are erratic; presumably these were caused by optically sized pinholes in the coating.

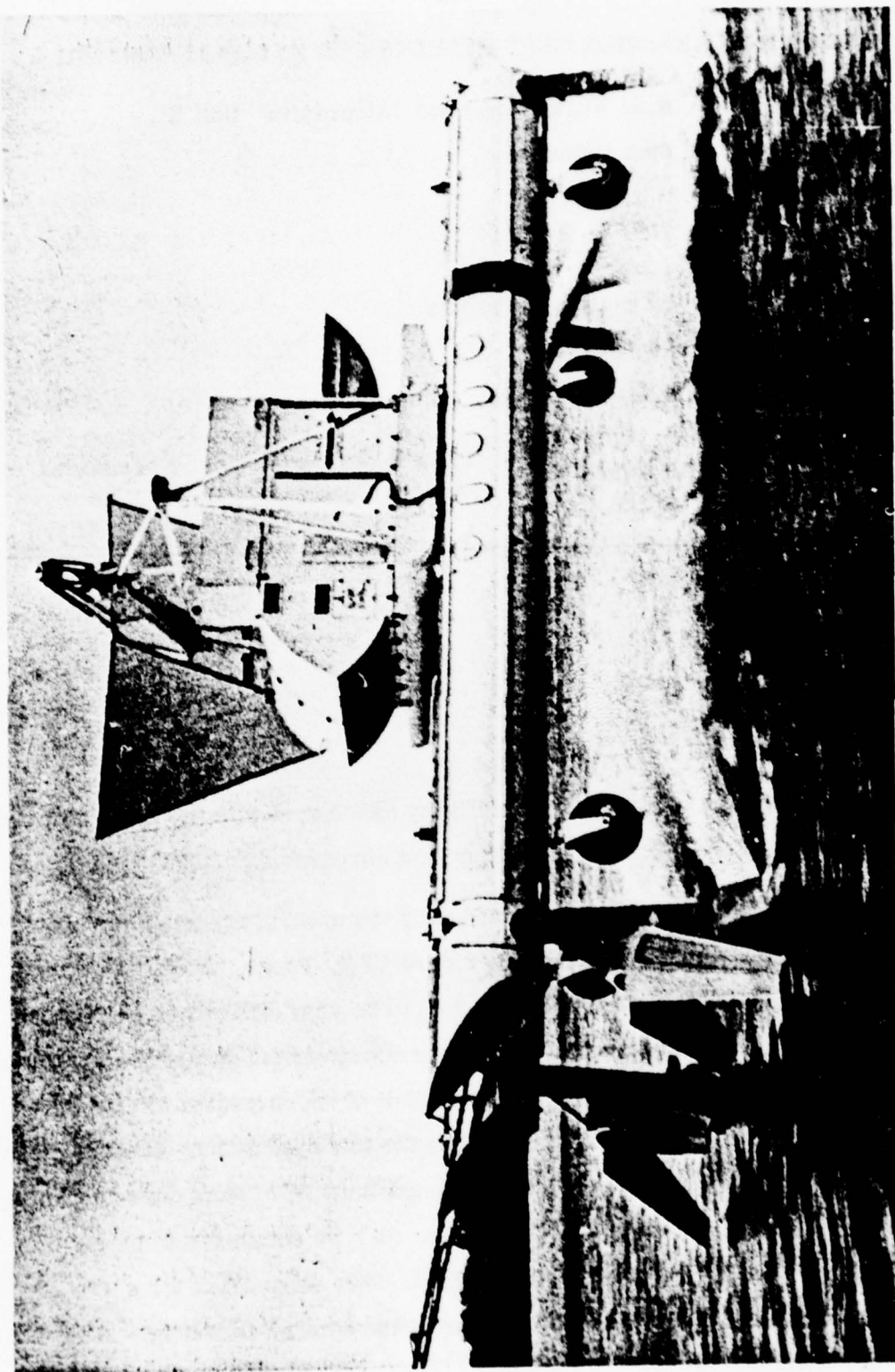


Figure VI-6. Minesweeping Sled Hydrofoils

TABLE VI-5. WATER VAPOR TRANSMISSION RATE TEST RESULTS

Material Tested	Material Method of Application	Film Thickness (Mils)	WVTR - *Duplicated Gms/100 In. ² /24 hrs.
Nylon 11	Electrostatic	7	0.422 and 0.543*
Nylon 11 (Smooth Surface Exposed)	Plasma	7	1.484 and 0.862*
Nylon 11 (Rough Surface Exposed)	Plasma	8	1.942 and 0.470*
Nylon 11 (Substrate)	Electrostatic	6	0.226 and 0.269*
Epoxy Primer (topcoat)	Wet Spray	2-3	
	Total	8-9	
Polyurethane Paint	Wet Spray	2-2.5	4.088 and 4.913*
Epoxy Primer	Wet Spray	1	2.397 and 1.561*
Polyurethane Paint (topcoat)	Wet Spray	2	
	Total	3	
Epoxy Primer	Wet Spray	6	0.730 and 0.784*
Epoxy Primer	Wet Spray	1-2	2.48 and 1.74*
Acrylic Lacquer (topcoat)	Wet Spray	4-5	
	Total	5-7	
Acrylic Lacquer	Wet Spray	3.5	7.52 and 8.10*

4. Wear Control

In service, aircraft control cables become corroded and frayed in locations where the cable passes over a pulley. A review of this problem revealed that 50% of the cables from one model of naval aircraft were corroded and had separated center core strands. Under the Naval Analytical Rework Program a new method was developed to improve the abrasion, fretting, and corrosion resistance properties of such control cables. The technique involves the vacuum impregnation of the interwoven steel-strand cables with anti-wear, anti-fretting, corrosion preventive grease (MIL-G-81322). After impregnation, the excess grease is wiped from the outer surfaces with a clean lint-free cloth moistened with hexane. A coating of primer is sprayed over the cable and allowed to air dry for 30 minutes. This is then overcoated with 3 mils of clear nylon 11 by electrostatic deposition, Figure VI-7. A comparative laboratory

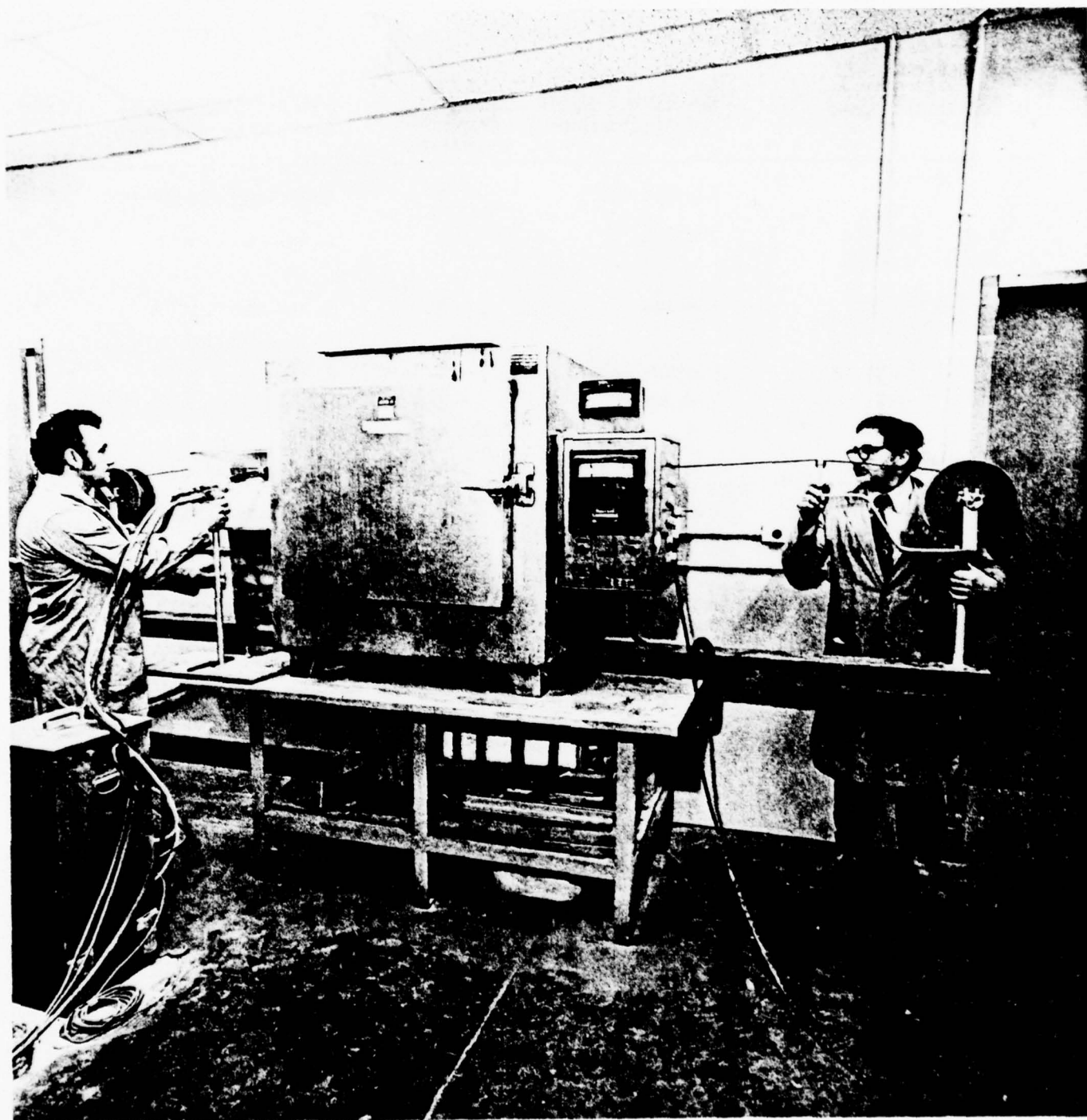


Figure VI-7. Electrostatic Deposition of Nylon 11 on Aircraft Control Cables

evaluation was conducted on the impregnated/encapsulated cables versus the conventionally treated cables. The test cables were subjected to 18 hours exposure to a 5% salt spray environment maintained at 100° F followed by a pulley test with a 331 pound load for 3000 cycles. Corrosion of the conventionally treated cables occurred after the second salt spray exposure (36 hours) with cable failure after 106,000 pulley cycles and 634 hours total salt spray exposure, Figure VI-8. The Analytical Rework Program cables, impregnated/encapsulated, showed no corrosion or failure after testing for salt spray exposure for 1364 hours and 225,000 pulley cycles, after which the testing was terminated, see Fig. VI-9.

Another type of wear control problem is that presented by spline assemblies. These are mechanical components designed to transmit power or drive accessories. Spline connections on aircraft power transmission shafts usually present stringent lubrication requirements. Such assemblies consist of two components, an external spline which mates with an internal spline. Because of this configuration, a misalignment of the two components will occur on installation or under dynamic operating conditions. A small amount of misalignment can be tolerated with the oscillatory motion caused by the misalignment and can be adequately controlled by proper lubrication.

In order to evaluate potential lubrication solutions to this problem, the Southwest Research Institute designed and built the spline wear tester, schematically shown in Figure VI-10. An internal test spline detailed in Figure VI-11 is clamped in a fixed position, and the flanged end of an external test spline is caused to gyrate without rotating, thereby simulating the relative oscillatory motions of a pair of angularly misaligned splines.

One approach that was investigated to alleviate spline wear involved the application of a nylon 11 powder coating. The external spline was undercut by 0.006 inches to allow for the nylon 11 coating build-up. A 0.006 inch coating of nylon 11 was deposited by electrostatic spray application. A molybdenum disulfide (MoS_2) diester grease was applied to the teeth of the external spline coated with nylon 11 and also to the teeth of an uncoated internal spline. This assembly was placed in the test apparatus

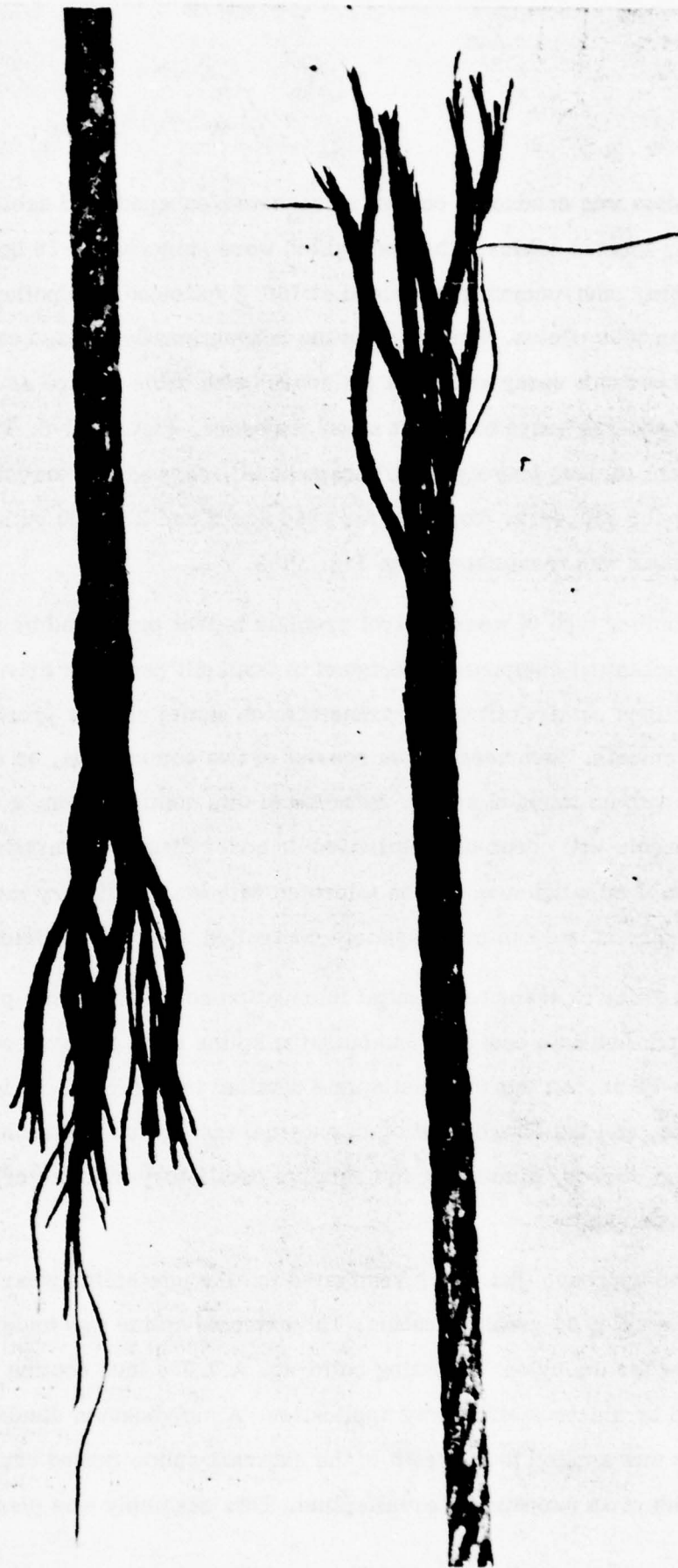


Figure VI-8. Cable Failure After Salt Spray and Fatigue Tests



Figure VI-9. Un-Failed Control Cable After Salt Spray and Fatigue Tests

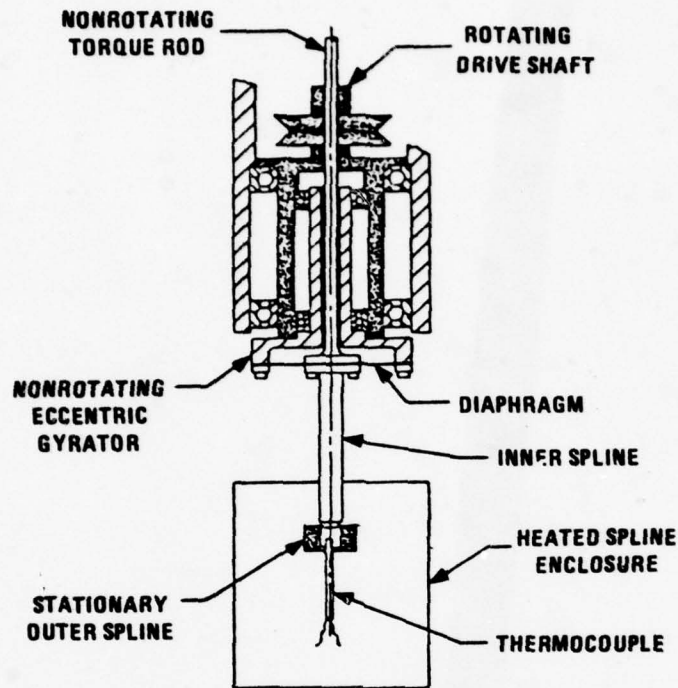


Figure VI-10. Schematic Representation of the Spline Wear Tester

and the test conducted under the conditions outlined above. Test results showed that a lubricated spline without a nylon 11 film is operational for 40 hours, while a spline treated with the nylon 11 film provides for 160 hours of operation under identical test conditions. In general, it is considered that the extended fatigue life obtained is a result of the low nylon 11 conforming elastically so as to permit a greater amount of actual surface contact without breaking through the lubricant film.

5. Conclusions

The applications of powder coating technology discussed in this paper are a few examples of typical Navy experience. From these specific applications, general conclusions reached are:

- Powder nylon 11 coatings will increase metal fatigue life over uncoated components without the disadvantages of other coatings, particularly presently used paint systems.

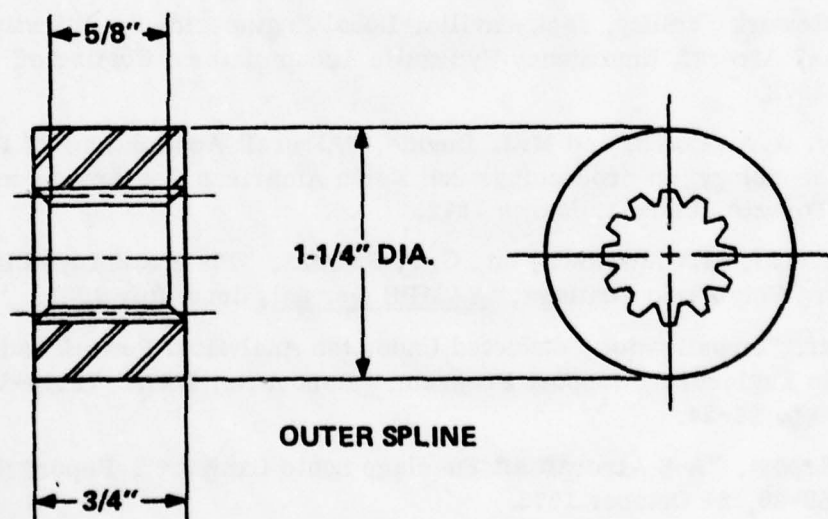
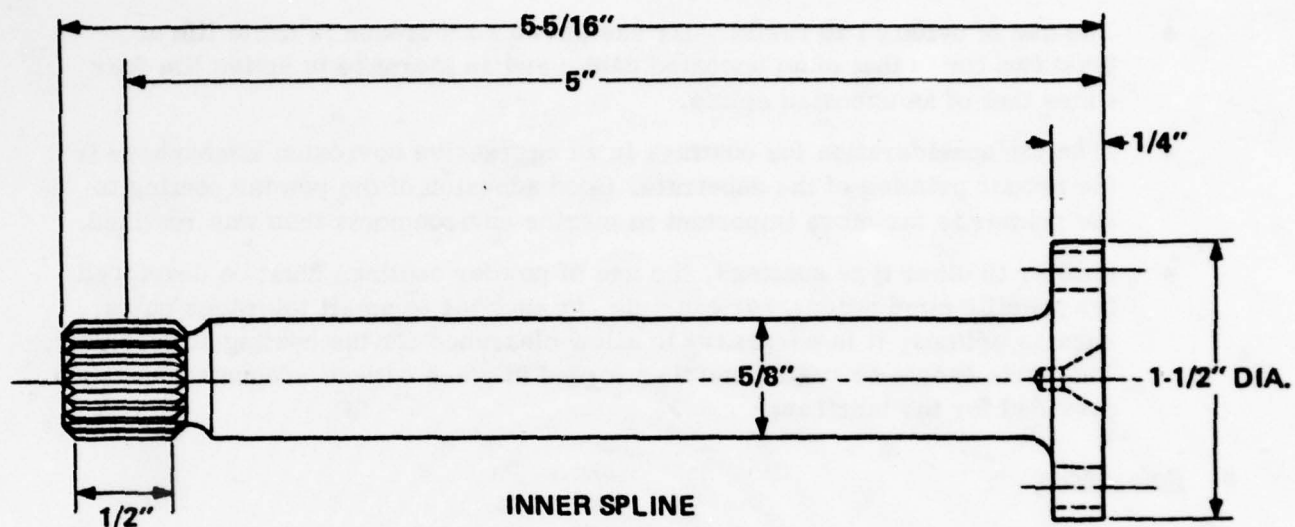


Figure VI-11. Detail of Standard Spline Specimen

- Nylon 11 is superior in abrasion/erosion resistance to other coatings and far superior to epoxy and vinyl paints.
- The use of nylon 11 to resist wear has shown an increase in cable life at least two times that of an uncoated cable; and an increase in spline life four times that of an uncoated spline.
- A major consideration for coatings in an aggressive corrosion atmosphere is the proper priming of the substrate. Good adhesion of the powder coating to the primer is far more important in marine environments than was realized.
- Similar to other type coatings, the use of powder coatings must be developed for specific application. For example, in applying to small tolerance parts, such as splines, it is necessary to allow clearance for the coating at assembly. The parts cannot be coated and then forced in place without adequate clearance provided for the lubricant.

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PART THREE: SEMINAR ACTIVITIES

Part three of the proceedings contain six chapters; one for each seminar held during the Workshop on Wear Control Technology.

Chapters VIII-XI include the recorded minutes of seminars #2-#5, the technical papers presented at those seminars, and a list of seminar participants.

Chapters VII and XII contain only a list of those individuals participating in seminars #1 and #6. It was decided by the participants of these seminars that they would accept, as official documentation of the seminar activities, their respective Chairman's Report. * Also, no technical papers were presented at these seminars.

*See Chapter II for the Chairman's Reports for the six seminars held at the Workshop on Wear.

CHAPTER VII

SEMINAR #1: AUTOMOBILES AND AUTOMOBILE SPARE PARTS

A. MINUTES OF SEMINAR #1

It was decided by the participants of seminar #1 that they would accept unanimously the report submitted by their Chairman. * As a result of this decision, no minutes were submitted for inclusion in the workshop proceedings.

B. TECHNICAL PAPERS PRESENTED AT SEMINAR #1

No formal technical papers were presented at seminar #1.

C. PARTICIPANTS/INVITEES AT SEMINAR #1

<u>Name</u>	<u>Affiliation</u>
F. F. Ling	Rensselaer Polytechnic Institute - Chairman
D. J. Barrett	Ford Motor Co.
W. Adams	Federal Mogul
R. L. Adamszak	USAF - WPAFB
F. W. Aldrich	Bendix Corp.
Robert Berke	National Association of Fleet Administrators
R. S. Dixon	TRW Replacement Division
D. R. Hays	GM Research
D. M. Hesling	Sealed Power Corp.
Warren R. Jensen	Raybestos-Manhattan, Inc.
E. Klaus	Pennsylvania State University
Hugh W. Larsen	General Motors Proving Ground
Drexel G. Minshall	Dana Corporation
John Nerlinger	Automotive Service Industry Association
J. Noettle	Automobile Club of Missouri
John Rumbarger	Franklin Institute Research Laboratory
L. Sibley	SKF Industries
Clark E. Stair	Firestone Tire and Rubber Co.

*The Chairman's Report for seminar #1 can be found in Chapter II, Section A.

CHAPTER VIII

SEMINAR #2: NAVAL AIRCRAFT STRUCTURES/MATERIALS/COMPONENTS

A. MINUTES OF SEMINAR #2

The seminar was opened by Chairman Koury who introduced the participants (see Section C of this chapter). Mr. Koury distributed copies of a workshop, "Proceedings of Materials/Processes 4th Annual Meeting - Wear Control for Naval Aircraft Under the Analytical Rework Program" and handouts describing the materials used as structural components in Navy aircraft. He stated that under the analytical Rework Program the Navy was aware of both the cost and significance of wear and had taken numerous steps to improve the durability of aircraft structures and components.

Mr. Koury then introduced Capt. Klett who described the Navy's service life program which has as its objective aircraft life extension. Previously aircraft were completely replaced after 10 years. Today obsolescence is not used, rather the life is defined by the structural fatigue resistance. Instrumentation is mounted on the aircraft so that the loadings and cycles on the critical components are defined. The stress/cycle limit is based upon Miner's rule for fatigue. A quarterly report is issued which defines the residual life in all aircraft. Aircraft functions are modified based on residual life. Capt. Klett also distributed a paper which described the present method of life cycle costing on aircraft tires and how it is used in the procurement of new tires. This paper emphasized that the life cycle cost concept for Navy tire procurement has motivated industry to provide tires with improved performance and reduced maintenance requirements.

In the discussion that followed this presentation, Mr. C. Troha of the FAA emphasized that the safe life structural design philosophy was generally not selected by the manufacturers to certify their commercial airplanes. In the design of military airplanes higher performance and shorter operating life generally dictate the safe life design philosophy. In commercial airplanes safety, long life and good economic performance dictate utilization of the fail safe structural design philosophy (multiple

load path structure); that is, efforts are directed to maximizing safety at economically feasible costs with superior operating performance. The fail safe philosophy relies heavily on the inspection and maintenance procedures of the operators to minimize catastrophic structural failure. Updating of NDT inspection technique and equipment would greatly improve safety with longer utilization of the airplane's structural components. The increasing cost of new airplanes is forcing the airline operators to evaluate the use of their older airplanes for as long as they can be safely operated. In this regard the FAA is evaluating the safety aspects of older airplanes to establish the structural modification necessary to assure their structural integrity for safe continuous service. As can be seen, economics determine to a large degree when an airplane is retired or modified to continue in service in some operation or another.

M. B. Peterson asked about interchangeability of parts which might reduce the materials required in supply and thus promote conservation. Mr. Pugh (Northrop) said that they did have such an approach on the F5 on which they could interchange the fuselage. Mr. Adams (Boeing) stated that they, too, had programs of interchangeability, for example, the nacelle is designed to accept different engines.

M. B. Peterson then described in detail how wear costs could be arrived at, using the maintenance information acquired by the Navy. Under an ARP program the total costs for wear were obtained on one Navy A6 for its tour of duty and its rework at the depot. The operational wear costs were obtained using the 3M data system. Here all maintenance actions are recorded and identified by malfunction codes. To obtain wear costs all wear related codes were used and a computerized printout was obtained for all wear related maintenance and material costs. This amounted to \$140/flight hour for unscheduled maintenance and \$67/flight hour for scheduled maintenance. Depot Rework wear costs are harder to categorize; however, they can be obtained. Each reworked part is associated with an individual card which tells precisely what was done and the number of man hours required to do it. It thus becomes necessary to determine the reason for rework for each part. In the example given the work cards for the aircraft in question were each discussed with the shop carrying out the rework and the cause of rework ascertained. The main causes were

wear, cracking, corrosion, torn surfaces, and testing. The wear costs (direct) were \$34.75/flight hour; material costs amounted to \$3.30/flight hour. Thus the total costs for wear on this aircraft were \$245/flight hour as compared with \$376/flight hour for fuel. Mr. Peterson pointed out that the significance of these numbers as far as this meeting was concerned was not how much wear cost but rather the fact that such information is available and can be assembled. He further pointed out that the high cost wear items did not represent the limits of technology but could be easily improved.

Mr. R. A. Kuzmick (NAILSC PAX RIVER) presented a program which they have developed to aid in making maintenance and logistics decisions. This program is called a Logistics Support Analysis (LSA). In essence this program computes the costs to the Navy of different alternatives. The total benefit can be computed based upon any proposed durability improvement. The program determines a component's optimal economical scheduled removal by comparing the penalty for an in-service failure (in terms of the increased cost requirement for performing unscheduled replacement as opposed to scheduled replacement) with the cost of lost, useful component life sacrificed as a result of a scheduled replacement policy. The program begins with failure rate data and includes cost factors attributable to labor, overhead, down time, materials costs, supply costs, etc. Decisions can be made on such questions as whether to repair a part or throw it away; where it should be repaired, should scheduled maintenance be performed, and whether improved designs are justified. This program could also be used to compute the benefits, both cost and material, of specific technological improvements. (Note -- It appears that this methodology will allow computation of the material and wear costs on a national basis as desired by OTA).

Following these presentations, discussions were held regarding wear problems and costs and how this industry practices wear control procedures.

Mr. E. Hargis of the U.S. Army Material Development and Readiness Command reviewed the various government programs and specifications available to improve equipment durability.

Mr. J. O. Trafton (GE) stated that contractors must now supply a list of all parts and materials and show that they will provide the required durability.

Mr. Pugh (Northrop) discussed their product services division which has the responsibility for incorporating new changes in aircraft. He further stated that the procurement specifications give general guidelines for design; if changes are to be made their specifications should be influenced.

Mr. Adams (Boeing) said that Boeing has experience retention programs which attempted to pass on part experience to the new generation engineers. He also said that they are now developing programs for materials conservation. For example, how to get the maximum number of parts out of a given piece of material. Mr. Pugh said they were involved in similar things; for example, using damaged materials in non-critical applications.

One of the impediments to better implementation of new technology and improved equipment durability is the annual review of costs and R&D allocations. This emphasized the start/stop syndrome. Longer range goals and programs should be established.

In general, it was concluded that aircraft are very sophisticated products and durability is only one factor that is considered in design, others being safety, performance, reliability, and economics. Although many examples could be given of improvements which could be made, these were not due to a lack of technology but rather due to a lack of communications since the user of aircraft were far removed from the designers. It was also agreed that there is very little wastage per se; however, a large material inventory is required to support aircraft in the field.

B. TECHNICAL PAPERS PRESENTED AT SEMINAR #2

1. "Naval Aircraft Fatigue Monitoring"

Just what is fatigue? Webster's gives two basic definitions both of which apply to our aircraft. Why is there so much more concern now over aircraft fatigue as

compared to 10 years ago? In 1954 the aircraft complement on the USS RANDOLPH consisted of Cougars, big and little Banshees, AD-4s, HUP for angel as well as a detachment of AJ-1s from time to time. About ten years later, on the INDEPENDENCE, there were F-4Bs, F-8s, A-4s, A-5s, an occasional A-3 from Rota and a UH-2B for angel. In the interim every aircraft on the RANDOLPH, except for the AD, had been retired, as had the FJ series, the F4D, F3H, and F7U. A recent carqual on the USS AMERICA hosted some modern aircraft, the A-7 and A-6, both introduced only about 10 years ago, but the RF-8G was also on board. As a look at another carrier would probably show, the F-4 is our main fighter strength, and the A-3, A-4, A-5 and H-2 are still in our very active inventory and some are projected to last for another ten years. Although helicopters have never formally been addressed as far as fatigue goes, the SH-3 was introduced in 1959 with a 13 year projected operating life. That 13 years was up for some aircraft four years ago. Helicopters present a whole new area which must be examined closely.

What this means of course is that not long ago aircraft became obsolete before they wore out. This is no longer the case and we are faced with longevity problems the same as humans. As more people reach old age we search for ways to keep fatigue critical components from wearing out - heart pacers, organ transplants, etc. We also recognize the additional tests required as we pass forty - annual EKGs, addition blood test for cholesterol, etc. As aircraft age it is also necessary to recognize that more intensive inspections are required and that extraordinary measures must be taken to retain their structural integrity.

What is the history of fatigue? Up until 1960 there was no real requirement, 2500 hours and 600 catapult shots being considered an old airplane. The A2F now the A-6A, was the first Navy aircraft for which a fatigue life was specified, 2500 hours, 1000 cats and arrests which was considered adequate. This has already been recognized as insufficient and it has been extended following testing and analysis. Today's requirement for tactical aircraft are 6000 hours and 2000 cats and arrests as a minimum with the contractor being required to continue his demonstration until

catastrophic failure. VR, VS and VP have a requirement for 15000 hours. Every aircraft in the Navy's inventory except for the S-3 and F-14, has had testing, analysis and subsequent fixes incorporated to give them the additional life required by operational necessity. It should be mentioned however, that there is no real fatigue hour limitation assigned to helicopter structure although dynamic components and rotor blades all have flight hour limitations prescribed.

Fatigue tests are concerned with two basic things, how long will the structure last, and where can it be expected to fail. These tests are conducted for the wing box and the catapult and arresting back up structure. One test on a TA-4J is currently underway at NADC, being done to determine how the loads imposed by the Blue Angels affect the fatigue lives of their aircraft. From this data applicable to the Blues, a better evaluation of the Fleet A-4's can be determined.

The severity of our testing takes into account both the anticipated frequency of "g" loadings as well as normal scatter. Since most aircraft will see a normal usage, aircraft are tested to a severe spectrum and then in effect derated. By tracking each aircraft's usage this conservatism can be cranked into additional lifetime in terms of hours. As failures occur in the fatigue test, the contractor is required to incorporate fixes which allow the aircraft to meet its fatigue goal. Test, Analyze and Fix, if you will.

Once the aircraft is in the fleet, the main task of tracking fatigue life starts. This is not a simple task but very important if all the life that has been built into the aircraft is to be safely extracted. For this purpose a counting accelerometer system is used consisting of an accelerometer unit and a counter which records numbers of exceedances at different "g" levels. There are now 5000 fixed wing aircraft monitored by NADC (Naval Air Development Center), of which a fatigue analysis is currently made for 3188.

The rationale behind using the information obtained from the counters is based on Miner's rule. Life expended is based on $\sum \frac{n}{N}$ rule where actual life is correlated to test data at various "g" levels and total life expended is calculated for each bureau

number. Theoretically, using a scatter factor of "two", an aircraft reaches its demonstrated fatigue life for the most critical component when $\sum \frac{n}{N} = 0.5$.

The data is entered monthly on a card for each aircraft and is then collected and analyzed by NADC. A quarterly report is prepared and distributed to cognizant activities for their information. A typical page provides a relatively complete fatigue history on every aircraft, including numbers of catapults and arrestments, of percent wing fatigue life expended and current fatigue expenditure rate.

Looking at total inventory, the accumulative rate of aircraft reaching their demonstrated fatigue lives based on hours alone is about twice that now experienced by use of an adequate fatigue monitoring program. The cost effectiveness is obvious.

2. "Economic Analysis Procedure" by A. J. Koury

The Economic Analysis is only performed when a component exhibits an increasing hazard rate with respect to time; since when the opposite exists, a scheduled removal policy would never be economically justified. The two factors that are weighed to determine a component's optimal economical scheduled removal interval are:

- The penalty for an in-service failure in terms of the increased cost requirement for performing unscheduled replacement as opposed to scheduled replacement.
- The cost of lost, useful component life sacrificed as a result of a scheduled replacement policy. This cost is dependent upon the interval of scheduled replacement, as well as the calculated hazard rate at that periodicity.

The Economic Analysis begins with an examination of the Statistical Analysis Program output (PTX-0417E). If the hazard rate of the "best-fit" distribution is increasing at any point in time, a cost analysis printout will be called out. It is in this output that the relationship between age and Failure Penalty (D) is established.

The next step in the Economic Analysis is to determine the Failure Penalty of an in-service failure, (D). The procedure for calculating D is explained in the Computation Instructions in the following section.

a. Computation Instructions for Economic Analysis

The cost analysis employed to calculate the penalty cost of an in-service failure is an adaptation of a technique found in "Rules for Planned Replacement of Aircraft and Missile Parts" by M. Kamins and J. J. McCall. There are two basic factors which affect the cost of replacement:

- (1) The cost of the downtime lost
- (2) The actual maintenance cost associated with replacement.

Both of these factors are likely to be higher for an unscheduled maintenance action than for a scheduled maintenance action. The cost of the downtime is often referred to as the opportunity cost since it represents the value of the output if no maintenance action has been required. The opportunity cost is likely to be higher for unscheduled maintenance for the following reasons:

- Longer periods are usually spent awaiting maintenance due to the unexpectedness of the event.
- The actual replacement time is usually longer since failed parts are more difficult to replace.
- The output lost during unscheduled maintenance is usually more valuable than that lost during scheduled maintenance. There are also several reasons for expecting the actual cost of maintenance to be greater for an unscheduled replacement.

A few of these reasons are:

- The replacement of a failed part is usually a more complex operation.
- Additional resources may be needed to repair parts damaged by failure.
- Maintenance resources may be required to be shipped to the site of the failure.

The following equations are used to calculate the Failure Penalty (D):

$$\begin{aligned} \text{Component Replacement Cost} = & \\ \text{Opportunity Cost} + & \\ (\text{Squadron Maintenance Cost}) + & \\ (\text{Intermediate Maintenance Cost}) + & \\ (\text{Depot Maintenance Cost}) & \end{aligned}$$

$$C_1 = O_p \times D_1 + S_1 \times L_s + (I \times L_i + K \times U) \times R_i + U \times R_{ci} + D_{rlm} \times R_d + U \times R_{cd}$$

$$C_2 = O_p \times D_2 + S_2 \times L_s + (I \times L_i + K \times U) \times R_i + U \times R_{ci} + D_{rlm} \times R_d + U \times R_{cd}$$

Where: C_1 = Total Cost of Component Scheduled Replacement

C_2 = Total Cost of Component Unscheduled Replacement

D = Penalty for an In-Service Failure

$$D = \frac{C_2 - C_1}{C_1} = \frac{C_2}{C_1} - 1$$

b. Definitions and Location of Parameters for Calculating C_1 : Parameter No. 1

O_p = Opportunity Cost, which represents the value of the time during which the aircraft is NOR (Not Operationally Ready) because of component replacement. The value of one hour of operationally ready capability is defined as the total cost of ownership divided by the total number of operationally ready hours in the planned service life:

$$O_p = \frac{I_n + (O_c \times SL)}{OR \times SL \times 365 \times 24}$$

Where:

I_n = Unit Investment Cost, found in NAVAIRINST 4710.12.

O_c = Removal Operating Cost Per Aircraft, calculated from the Navy Program Factors Manual.

SL = Planned Aircraft Service Life in Years, found in OPNAVINST 3110.11G.

OR = Planned Operational Ready Rate, found in OPNAVINST 5442.4C.

c. Parameter No. 2

D_1 = Expected Aircraft Downtime for Scheduled Maintenance (i.e., the elapsed time to remove and replace the component and adjust, calibrate and check the system). This is found in the Maintenance History Summary (Program 0438N).

d. Squadron Maintenance Cost

Squadron Maintenance Cost represents all 0-level costs associated with the component replacement. The equation presented ($S_1 \times L_s$) assumes the normal case where labor only is supplied at the 0-level.

e. Parameter No. 3

S_1 = Squadron Maintenance Man-Hours (Scheduled). Find S_1 in the Maintenance History Summary (0438N).

f. Parameter No. 4

L_s = Average Cost for One-Hour Squadron Labor. Use \$21 for L_s . This figure is based on average costs for 0-level maintenance billets as given in NAVPERS 15163, converted to an hourly basis using 120 work-hours per month multiplied by 1.14 to convert 3-M MMH (Maintenance Man-Hour) to billet work-hours. Indirect support personnel costs were assumed at a 1.83 to 1 ratio (i.e., total = 1.83 direct cost).

g. Intermediate Maintenance Cost

Intermediate Maintenance Cost represents labor and materials used in repair of the component multiplied by the fraction of total removals repaired at the intermediate level, plus the fraction of total removals condemned at the Intermediate level multiplied by the component unit cost.

h. Parameter No. 5

I = (Intermediate Maintenance Activity) Repair Direct Maintenance Man-Hours. I is found in the Maintenance History Summary (0438N).

i. Parameter No. 6

L_i = Average Cost for One-Hour Intermediate Labor. This figure is based on average costs for I-level maintenance billets and calculated the same as L_s . Use \$23 for L_i .

j. Parameter No. 7

$K = \text{IMA Repair Parts and Materials Factor}$. Estimate K as a percentage of SRC unit procurement cost, or use 25%.

k. Parameter No. 8

Obtain U by locating the part number or federal stock number in the Federal Supply Catalog, or use alternate source for average unit procurement cost (e.g., Station Supply, etc.).

l. Parameter No. 9

$R_1 = \text{Fraction of Components Repaired at the IMA}$. R_1 is found in the Maintenance History Summary (0438N).

m. Parameter No. 10

$R_{c1} = \text{Fraction of Components Condemned at the IMA}$. R_{c1} is found in the Maintenance History Summary (0438N).

n. Depot Maintenance Cost

Depot Maintenance cost includes labor and materials for repair of the component at Depot multiplied by the fraction of total removals repaired at the Depot, plus the fraction of total removals condemned at Depot multiplied by the Unit Cost. Transportation costs to and from Depot plus storage, etc., have not been included. If average costs by part number are known for these actions, they should be added to the Depot maintenance cost calculated below.

o. Parameter No. 11

$D_{rlm} = \text{Depot Repair, Labor, and Material Cost for a Single Component}$. To obtain this figure, multiply: Standard Time to Repair x NIF rate (latest available, includes overhead, parts and labor) for a component.

The above information should be available at the NARF Comptroller Shop. If not available, use $D_{rlm} = 1.2 U^{0.784}$ where U = Unit Procurement Cost.

p. Parameter No. 12

R_d = Fraction of Components Repaired at the Depot Level. R_d is also found in the Maintenance History Summary (0438N).

q. Parameter No. 13

R_{cd} = Fraction of Total Items Processed that were Condemned at the Depot Level.
 R_{cd} is found in the Maintenance History Summary (0438N).

NOTE: One of the inputs to this program for obtaining R_{cd} is the percentage of items condemned at the Depot. This number can be found in the FSN versus IIC No. Report, which should be located in the F/J section of the NARF.

A recommended check to determine the accuracy of the data and/or program is to utilize the following equation:

$$R_1 + R_{cl} + R_{cd} + R_d = 1$$

It is recommended that the results of the program not be used should this equation add to less than .96.

r. Definitions and Location of Parameters for Calculating C_2 :

The calculation of C_2 is performed the same as C_1 , except that D_2 and S_2 are substituted for D_1 and S_1 .

s. Parameter No. 14

D_2 = Expected Aircraft Downtime for Unscheduled Maintenance. That is, the elapsed time to inspect, test, trouble-shoot, and isolate the failure in the system (or next higher assembly); plus remove and replace the component, plus adjust and calibrate the system. In addition, a 1.0 hour awaiting parts planning factor must be added. D_2 is found in the Maintenance History Summary (0438N).

t. Parameter No. 15

S_2 = Squadron Maintenance Man-Hours (Unscheduled). Includes total time to inspect, test, troubleshoot, and isolate the failure in the system (next higher assembly); plus remove and replace the failed component; plus adjust, calibrate and check the system as required after installation of the new components. S_2 is found in the Maintenance History Summary (0438N).

By substituting the preceding parameters, the equations for C_1 and C_2 can be calculated. The next step is to substitute C_1 and C_2 into the given equation to obtain the Penalty for an in-service failure, D:

$$D = \frac{C_2}{C_1} - 1$$

To aid in the calculation of D an Economic Analysis Data Summary Sheet is recommended, shown in Figure VIII-1. "Optimum Replacement Intervals" printout (program 0417E) to obtain the corresponding optimum economic removal time for the SRC component.

C. PARTICIPANTS/INVITEES AT SEMINAR #2

<u>Name</u>	<u>Affiliation</u>
A. J. Koury	NAVAIR, Washington, D.C. - Chairman
A. C. Daniels	GE, Pittsfield
W. M. Capece	NADC, Warminster
G. J. Klett	NAVAIR, Washington, D.C.
C. Troha	FAA - ARD - 520
C. R. Adams	Boeing
R. H. Pugh	Northrop/Aircraft Division
J. O. Trafton	GE - ASD
R. S. Miller	ONR
G. H. Kitchen	Bell Labs
A. W. Jones	Wayne State University
E. Hargis	U.S. Army Material Dev. & Readiness - CMD
M. B. Peterson	Wear Sciences Inc.
G. C. Perlmutter	Bradford Company & Systems
R. A. Kuzmick	NAILSC PAX RIVER
P. Nannelli	Pennwalt R&D
J. John	IRT Corporation, San Diego

FOR A/C T/M/S _____

NOMENCLATURE _____

PART NUMBER _____ WUC _____

$$\text{LET } D = \frac{C_2 - C_1}{C_1} = \frac{C_2}{C_1} - 1$$

D = penalty for an in-service failure

C_1 = total cost of component scheduled replacement

C_2 = total cost of component unscheduled replacement

Component Replacement Cost

= Opportunity Cost + Squadron Maintenance Cost + Intermediate Maintenance Cost + Depot Maintenance Cost

$$C_1 = O_p \times D_1 + S_1 \times L_s + (I \times L_1 + L \times U) \times R_1 + U \times R_{ci} + D_{rlm} \times R_d + U \times R_{cd}$$

$$C_2 = O_p \times D_2 + S_2 \times L_s + (I \times L_1 + K \times U) \times R_1 + U \times R_{ci} + D_{rlm} \times R_d + U \times R_{cd}$$

PARAMETER	DEFINITION	PARAMETER NUMBER	VALUE
O_p	Hourly Aircraft Downtime Opportunity Cost Penalty	1	-
	$O_p = \frac{In + (Oc \times SL)}{OR \times SL \times 365 \times 24}$		
	Where:		
	In = Aircraft Unit Investment Cost	1	-
	Oc = Annual Operating per Aircraft	1	-
	SL = Planned Aircraft Service Life in Years	1	-
	OR = Planned Operational Ready Rate	1	-

Figure VIII-1. Economic Analysis Data Summary Sheet

PARAMETER	DEFINITION	PARAMETER NUMBER	VALUE
D_1	Expected Aircraft Downtime for Scheduled Maintenance	2	-
S_1	Squadron Maintenance Man-Hours (Scheduled)	3	-
L_s	Average Cost for One Hour Squadron Labor	4	-
I	IMA (Intermediate Maintenance Activity) Repair Direct Maintenance Man-Hours	5	-
L_i	Average Cost for One Hour Intermediate Labor	6	-
K	IMA Parts and Material Factor	7	-
U	Unit Procurement Cost of the Component	8	-
R_i	Fraction of Components Repaired at the IMA	9	-
R_{ci}	Fraction of Components Condemned at the IMA	10	-
D_{rlm}	Depot Repair, Labor, and Material Cost	11	-
R_d	Fraction of Components Repaired at the Depot Level	12	-
R_{cd}	Fraction of Total Items Processed Which Were Condemned at the Depot Level	13	-
D_2	Expected Aircraft Downtime for Unscheduled Maintenance	14	-
S_2	Squadron Maintenance Man-Hours (Unscheduled)	15	-

Figure VIII-1. Economic Analysis Data Summary Sheet (Continued)

Substituting into the given equations:

$$C_1 = \underline{\hspace{10cm}}$$

$C_2 =$ _____

D = _____

Now referring to the computer printout (PTX04-17D) of D as a function of the optimum economic removal interval

The optimum economic removal interval = _____

Figure VIII-1. Economic Analysis Data Summary Sheet (Continued)

CHAPTER IX

SEMINAR #3: AIRCRAFT/AIRCRAFT PROPULSION SYSTEMS AND COMPONENTS

A. MINUTES OF SEMINAR #3

1. General

The seminar on wear control in aircraft propulsion systems was held in three consecutive sessions, totalling about nine hours of discussions. There were 16 participants, representing aircraft engine and helicopter transmission manufacturers, bearing and petroleum industries, commercial airline and military users, U.K. and other U.S. Government organizations, and university and research institutes.

In opening the morning session, P. M. Ku, chairman, thanked the participants for answering the call from the Office of Technology Assessment on short notice. He indicated that he learned much from the background sessions of the preceding day, and looked forward to the equally informative discussions on the subject of wear control in aircraft propulsion systems from the experts present.

He recalled that he received the invitation from OTA on January 26, and on January 29 wrote to those on the original list of participants, soliciting their advice regarding the conduct of Seminar #3 and also requesting information as to who might have "prepared briefs" to present so that he could pace the discussions effectively. On the basis of the replies he received, he would devote the morning session to general discussions on wear control, the afternoon session to life-cycle cost and related topics, and the evening session to reviewing his proposed summary report for the following day.

2. Importance of Wear Control

In order to put the subject of wear control in its proper perspective, Mr. Ku referred to a letter from Mr. B. M. Meador of TWA, dated February 4, who expressed his regrets for not being able to attend this Workshop, and stated additionally that "While wear is certainly one of the elements of materials degradation

which we must consider, I might point out that it is not the most critical element of the several that we face in the operation of aircraft and aircraft propulsion systems. While we would like to see technological developments in the area of improved wear control, it is not the most outstanding need we face at this time."

Mr. Ku then recalled the very fine presentation made on the preceding day by Mr. T. Matteson of United Airlines, in which the latter distinguished between "reliability" and "safety" in airline service, and due to the high degree of redundancy employed to achieve safety, it was implied that "reliability" became somewhat of a hidden economic issue. Mr. Ku wondered just how important wear control was as an economic factor in commercial airline operations and, for that matter, in military operations. In particular, he wondered what the situation might be for single-engine aircraft and helicopters, for which "reliability" and "safety" were synonymous.

Mr. Dow replied that Eastern Airlines did not have the biggest losses in the wear area. He emphasized that aircraft engines were 10 or more years ahead of other industry improvements, hence the benefits of wear control were less apparent.

Mr. Jones remarked that the Air Force considered the reliability and economic aspects of wear control as very important. He further stressed the importance of nondestructive inspection of engine components, as inexpensive weak parts might result in critical failure of the entire aircraft. He said that the military was tending toward on-condition maintenance. Where scheduled maintenance was used, there were problems in the storage and handling of spare parts and in determining the serviceability of the parts removed during scheduled maintenance.

In the general discussions which followed, it was agreed that the benefits to be derived from effective wear control were alike regardless of the nature of aircraft service. These benefits were as follows:

- Reduced maintenance and replacement costs.
- Improved propulsion system performance and fuel cost.

- Conservation of critical materials.
- Technology spin-off, which benefits other industries.

It was pointed out that aircraft propulsion (engines and transmissions) was currently a \$4-billion dollar industry. A recent study conducted by the Navy on the operating costs of one aircraft* showed that the total cost of wear was \$245/flight hour as compared to the total cost of fuel of \$376/flight hour. Of course, the propulsion system was not the sole contributor to the total cost of wear on an aircraft. So far as the propulsion system alone was concerned, it was the consensus of the participants that with adequate development and Governmental encouragement, savings of 50% in materials, 10% in fuel consumption, and at least 50% in maintenance and replacement costs, could be realized within one decade.

3. General Discussion on Wear Control

a. Engines

Mr. Schevchenko stated that the engine manufacturers were cognizant of the importance of wear control problems.

Professor Johnson said that he had conducted a survey of the wear control problems and technology status for aircraft engines, a brief summary of which was presented (see Table IX-1).

b. Helicopter Transmissions

Mr. Bowen commented on the material needs of helicopter transmissions, provided a historical perspective to the advances made in extending the overhaul interval, and discussed the potential wear life increases (see Section B of this Chapter).

Mr. Lemanski pointed out that about 12-13 million dollars had been spent in recent years on research and development in the helicopter transmissions area,

*"Proceedings, Wear Control for Naval Aircraft," Naval Aircraft Materials/Processes Meeting, 4th Annual Meeting, Aeronautical Analytical Rework Program, 2-4 Dec. 1975, Naval Air Development Center, Warminster, Pa.

TABLE IX-1. REPORT - R. L. JOHNSON (RPI) - WEAR CONTROL PROBLEMS AND TECHNOLOGY STATUS

PROBLEM	SYSTEM	TECHNOLOGY STATUS FOR REDUCING WEAR
Abrasive dirt ingestion	Engine - Compressor ingestion abrades gas path blading.	Major cost item - Compressor blades. Abrasive wear technology is deficient but is essentially ignored by engine designers in selecting abrasion resistant materials. New research on abrasive wear is required.
Contamination	Engine - Lubrication system From atmosphere and gas path airflow - through seals and vents promoting abrasive and corrosive wear of all lubricated components.	Contact seals mishandled in maintenance and labyrinth seals are ineffective. Labyrinths do not exclude dirt and often are staged and pressurized with external gas path bleed air that is loaded with dirt. Labyrinths should be discarded for close clearance scale. Better filtration of oil and debris exclusion devices are needed. Development required.
Condition monitoring	Engine - Lubrication and hydraulic systems. Sensing wear debris, dirt, moisture, cleaning solvent contamination, lubricant decomposition including additive depletion.	SOAP analysis, ferrography, x-ray fluorescence, system operating parameters, etc. have shown value for monitoring "on-condition" maintenance but are inconvenient and costly. Simple on-board monitoring method with improved fluid filtration and reconditioning practices are needed.
Lubricant consumption and hazards	Engine - Lubrication system Hot air leakage passed labyrinth seals into sump.	Oil air mist is lost overboard giving oil consumption for labyrinth engines several times that of engines with nominal contact seals. If high temperature compressor air goes into sumps, lubricant degradation is accelerated and sump fires may occur. Degraded lubricant products accelerate wear. More oxidatively stable lubricants would reduce potential problems. Fluids and systems research needed but mostly labyrinth seals should be eliminated.

TABLE IX-1. REPORT - R. L. JOHNSON (RPI) - WEAR CONTROL PROBLEMS AND TECHNOLOGY STATUS (Continued)

PROBLEM	SYSTEM	TECHNOLOGY STATUS FOR REDUCING WEAR
Wear of mechanical components	Engine mainshaft and accessory systems (seals, gears, bearings)	Primary effort to improve sealing practice needed. High technology seals are available but need development for special problem areas and retrofit programs. Most wear problems are from contaminants (i.e., dirt). Solutions can be demonstrated with better filters, good seals. More attention to thermal control (i.e., cooling) is needed for all components to prevent lubricant and component thermal degradation.
Wear of gas path shrouds and blades	Engine - gas path	Major cost item - turbine blades. Minimum tip clearance needed for turbine and compressor blades. Rubs against shroud cause costly tip wear with thermal and mechanical excursions of shaft and blading. Present development shroud materials are porous and give flow losses. Compliant sacrificial shrouds needed to prevent blade tip wear.
Fretting and fretting induced fatigue	Shafting splines, blade mountings, dampers, seals clutches, fasteners, slip joints, threads, and raceway keys or lugs.	Always a nuisance and often critical. Hardening, solid and liquid lubricants usual design approach. Use of adhesion technology and fundamental surface chemistry and coatings with propagation of fatigue failures need research and application.

but much of the information was buried in the libraries and not effectively used. As to the future, he felt much could be done to reduce maintenance (see Section B of this Chapter).

c. Bearings

Mr. Sibley reviewed the progress made in the bearing industry and also noted the technology improvements that appeared to be on the horizon (see Section B of this Chapter).

d. Seals

Mr. Ludwig reviewed the current status of gas-path and liquid seals, and pointed out the technology gaps that required bridging (see Section B of this Chapter).

Upon returning from lunch, the participants attempted to answer the following questions in the Prospectus:

Are optimum wear control procedures followed in your industry? The answer from the commercial airline sector was a qualified "yes," with on-condition maintenance. However, it was pointed out that the procedure could be improved if reliable condition monitoring instrumentation were available. The process could also be made more efficient with improved labor skills and motivation.

The answer from the military sector was also a qualified "yes," with the military generally changing over from scheduled maintenance to on-condition maintenance. In addition to the problems faced by the airlines, the storage and handling of replacement parts in the military supply system were difficult. Moreover, where scheduled maintenance was practiced, reliable determination of the usability of the removed parts also presented a problem.

If optimum wear control procedures are not used, why? This question evoked a considerable amount of discussion. The general consensus was that, by and large, the problem was not one of lack of basic available knowledge, but a lack of timely technology transfer in usable form. On the design side, due to a lack of adequate

financial support for intermediate development, the design had tended toward conservatism. On the maintenance side, current knowledge should be put into practice and improved technology (such as in-flight condition monitoring) should be sought to provide further advances.

It was felt that Governmental support might possibly be directed along the following lines:

- Taxation and accounting policies designed to encourage savings in maintenance cost and materials conservation.
- Better balance and simplification of regulatory procedures.
- Direct financial support to accelerate the tempo of improvements, particularly in the area of intermediate development mentioned above.
- Direct financial support in research in critical areas.

Can products be made to last longer? The consensus was a resounding "yes."

It was pointed out that we should identify the various failure processes and have a better understanding of their impact, which would help in the long run. However, even on the short range, the research laboratories had shown that new materials and lubricants with substantially better wear and other attributes had become available, even though these were not necessarily the ultimate obtainable. By merely taking advantage of these available new materials and lubricants, and with improved designs, the engine and helicopter manufacturers had proposed designs which, given timely and adequate financial support, could, within one decade, yield estimated savings of 50% in materials, 10% in fuel consumption, and at least 50% in maintenance and replacement costs.

4. Life-Cycle Cost

Mr. Ku then directed the attention of the group to the subject of life-cycle cost, expressing his concern about the difficulties in predicting the inflation of the dollar and the capricious nature of the fuel cost. He then asked Mr. Shevchenko and Mr. Bowen to continue on their prepared briefs.

Mr. Schevchenko remarked that the Sallee report cited in his prepared brief brought out two interesting points: (a) During the initial 5-year period after a new design had been put into service, the maintenance cost was high. However, during the "mature period" after the initial problems had been solved, the maintenance cost reduced to about one-half to one-third of the initial. (b) There was no significant difference between military-derived vs. commercially-derived propulsion systems in life-cycle costs.

The group believed that the high initial maintenance cost cited above was due to the lack of intermediate development previously mentioned. In the instance of commercial airlines, this meant in effect that the airlines would pay for the lion's share of the intermediate development cost, which cost must in turn be passed on to the customers. In the case of military service, the cost of intermediate development would in effect be borne by the Government, or the general public. Perhaps direct Government support of intermediate development would be more effective and more economical in the long run.

In the general discussion which ensued, it was agreed that consideration should be given to the impact of mission profile, i.e., short missions vs. long missions, as the problem here was akin to the stop-and-go automobile operation vs. sustained highway driving. Moreover, the impact of propulsion system performance and performance degradation in service might be important. In this respect, the relative weight to be assigned to cost and performance might well be different for commercial and military operations. There was also the question of initial equipment cost vs. spare parts cost, i.e., how to achieve a realistic balance between them? Finally, there was the question of warranty. The current commercial procurement practice was for the propulsion system manufacturer to assume the warranty responsibility, while in Government procurements the responsibility rested, with some isolated exceptions, with the Government. How would these different procurement practices affect the life-cycle cost?

5. Wear Control Programs and Implementation

With reference to the last two questions posed in the Prospectus, it was felt that the commercial airlines' on-condition maintenance indicated a qualified "yes," but improvements could be made as pointed out earlier. The answer from the military sector was also a qualified "yes," with the Navy having already implemented on-condition maintenance, but as yet not enough experience to provide details. The Air Force and the Army were tending toward this direction, with on-going programs on reliability and maintainability studies.

It was pointed out that the wear control technology was generally implemented in both the design and maintenance processes, but not separately identified in the organizational structure.

6. Summary Report

During the evening session, Mr. Ku said that he, Mr. Gavert, and Mr. Roeser had met to review the notes that they each took during the two preceding sessions. He then read the proposed summary report and asked for comments and suggestions for improvement, and finally concurrence of those present.

Valuable suggestions for improvement were received. These were reflected in the final version of the report.

B. TECHNICAL PAPERS PRESENTED AT SEMINAR #3

1. "Helicopter Propulsion Systems" by C. W. Bowen

a. Critical Materials

The modern helicopter drivesystem use of metals does not encompass a particularly wide range. In general there are three classes of metal materials. The case and through hardening steels used for gears and bearings, the medium hard grades steels (and occasionally Titanium) used for shafts, carriers, and fasteners, and the low density aluminum and magnesium alloys used so extensively for the housings and cases. Those in current use may be summarized as follows:

CASE THROUGH
HARDENING

MEDIUM HARD

LIGHT ALLOYS

AMS 6470

AISI 4340

A356-T6

AMS 6475

AISI 4140

AMS 6260

AISI 4130

KO-1

AISI H-11 Mod.

AISI H-12 Mod.

6Al-4V

AZ91-T6

AISI M-50

18 Ni 250 Mar.

ZE41A-T5

AISI 52100

17-4PH

QE22A-T6

AISI 8620

AISI 8822

The significant elemental constituents of the more commonly used materials from the above list are contained in Figure IX-1. The four most critical alloying constituents mentioned in the Prospectus for this Workshop on Wear are emphasized in heavy block outline.

Other materials have been the subject of much research and experimentation in the past decade. USAAMRDL and NASA Cleveland have been instrumental in encouraging the use of high hot hardness materials in order to assist in successful operation under marginal lubrication - although there is less than unanimous agreement amongst industry on the suitability of most candidate materials. Some of these materials and their elevated temperature hardnesses are shown in Figure IX-2.

It is obvious from Figure IX-1 that the family of high hot hardness materials all use higher concentrations of Chromium than the more traditional materials.

However, relative to certain consumer product categories, the absolute quantities of the listed critical materials used in the past 15 years for helicopter transmissions are not very great. I estimate them to be on the order of (in tons):

Material Designation	Material Description	Alloying Constituents (Elemental) in Percentage												Material Usage
		C	Cr	Ni	Mo	Al	Mg	Fe	Mn	Si	Cu	Zn	Other	
356-T6	Al. Alloy (Casting)	--	--	--	--	Bal.	.03	.50	.10	7.0	.20	.20	--	Cases, Housings Supports
AZ91C-T6	Mag. Alloy Casting	--	--	.01 Max.	--	9.0	Bal.	--	.13	.30 Max.	.10 Max.	1.0	--	Cases, Housings Supports
ZE41A-T5	Mag. Alloy Casting	--	--	.01 Max.	--	--	Bal.	--	.15 Max.	.01 Max.	.10 Max.	4.0	Zr 0.7 Ce 1.2	Cases, Housings Supports
QE22A-T6	Mag. Alloy Casting	--	--	.01 Max.	--	--	Bal.	--	.15 Max.	.01 Max.	.10 Max.	--	Zr 0.7 Re 1.7 Ag 2.5	Cases, Housings Supports (Re=Didymium)
AMS 6260	Carburizing Steel	.10	1.2	3.25	.10	--	--	Bal.	.55	.30	--	--	--	Gears, Couplings Shafts
AMS 6470	Nitriding Steel	.40	1.6	--	.35	1.10	--	Bal.	.60	.30	--	--	--	Gears, Couplings
AMS 6475	Nitriding Steel	.23	1.1	3.50	.25	1.25	--	Bal.	.60	.30	--	--	--	Gears, Couplings
SAE 4130	Thru Hardening Steel	.30	1.0	--	.20	--	--	Bal.	.50	.30	--	--	--	Shafts, Carriers Bolts, Washers
SAE 4140	Thru Hardening Steel	.40	1.0	--	.20	--	--	Bal.	.80	.30	--	--	--	Shafts, Carriers Bolts, Washers
SAE 4340	Thru Hardening Steel	.40	.80	1.80	.25	--	--	Bal.	.70	.30	--	--	--	Shafts, Carriers Bolts, Washers
SAE 52100	Thru Hardening Steel	1.00	1.45	.35 Max.	.08 Max.	--	--	Bal.	.35	.30	--	--	--	Rolling Elements Bearings
M-50	T. H. & C. H.	.80	4.0	.01 Max.	4.25	--	--	Bal.	.35 Max.	.25 Max.	--	--	--	Rolling Elements Bearings
H-11	T. H. & C. H.	.35	5.0	0	1.3	--	--	Bal.	.30	.90	--	--	--	Gears, Couplings
H-12	T. H. & C. H.	.35	5.0	0	1.4	--	--	Bal.	.30	.90	--	--	Wo 1.4	Gears, Couplings

Figure IX-1. Most Common Use - Helicopter Transmission Materials

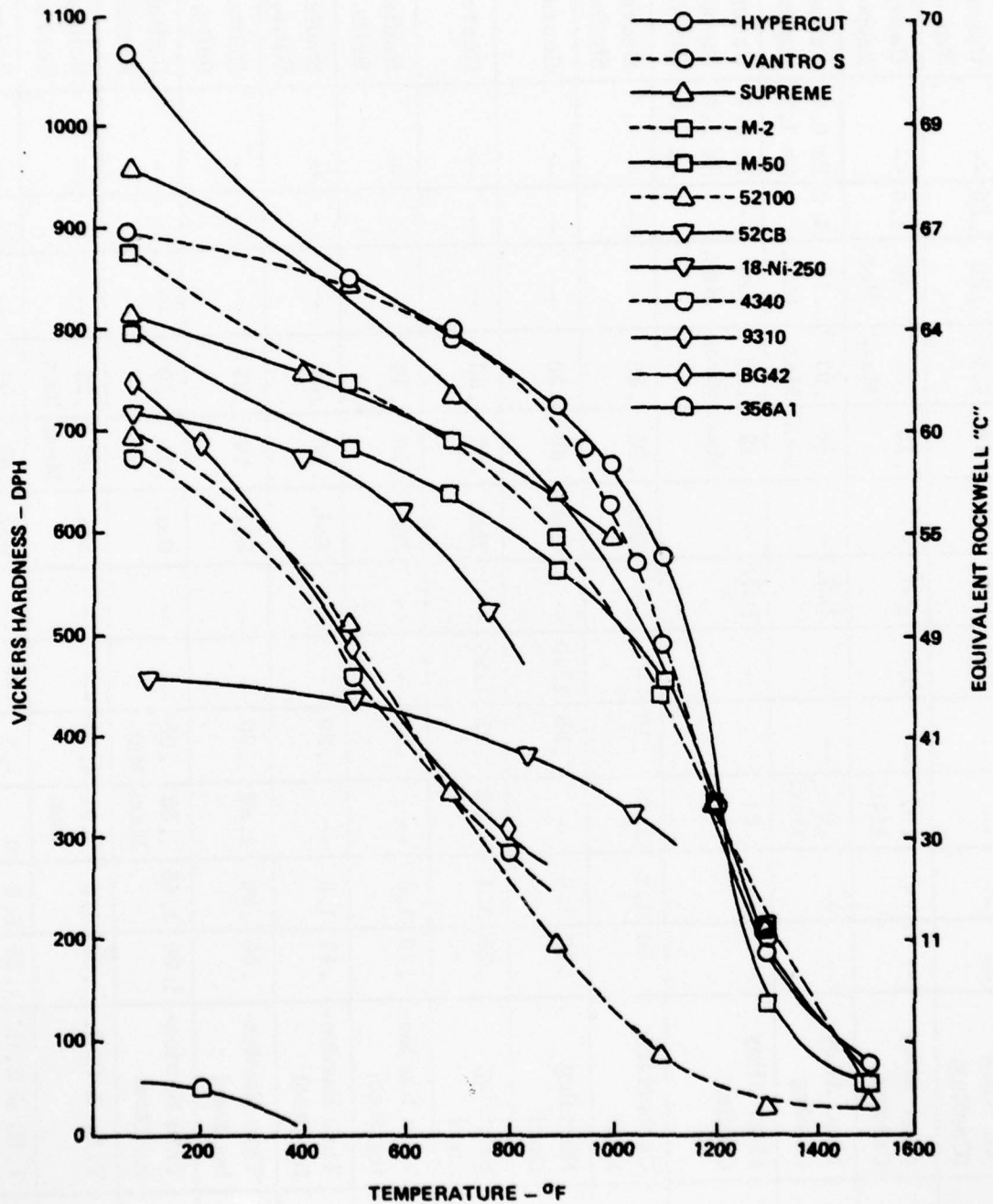


Figure IX-2. Hot Hardness of Some Aerospace Materials

<u>STEEL</u>	<u>CHROMIUM</u>	<u>ALUMINUM</u>	<u>COPPER</u>	<u>NICKEL</u>
100,000	1,600	3,000	*2,200	2,200

*Of this figure about 220 tons were used in the transmission and 2,000 tons in process.

These amounts represent the mill runs - not the finished product. Due to scrap turning, remelt, and salvage practices employed in the industry about 75% of these quantities probably have been salvaged.

b. Historical Perspective

The operational hours between scheduled overhaul for helicopter transmissions has progressed from the 50/100 hour category of the 1940's when they were first licensed to the 1000/2000 hour range of today. Figure IX-3 shows the progression of TBO for certain Bell Helicopter machines which are typical of the industry.

This was a loaded statement - it should be emphasized that equipment life need only be as good as the competition! It has historically been very difficult for the engineer to sell life cycle cost reduction as a reason for any design improvement.

Our industry, like all other consumer product groups, has been consumption oriented for some of these following reasons:

- Procurement specification priorities:

These always rank performance first. The procurement unit costs are targeted - and since contracts cannot be awarded on life cycle costs (unless your crystal ball is better than ours) - the procurement contracts go to the lowest bidder when performance levels are comparable among the competitors.

- Profit and GNP rationale:

Spares are great business. No more non-recurring costs - engineers and tooling costs are long gone - nothing left but profit. Is there a design engineer (over thirty) among us who has not heard, "Oh, well, it's good for the Gross National Product," in reply to a specific query about the wastefulness of a particular program in which he reluctantly participated?

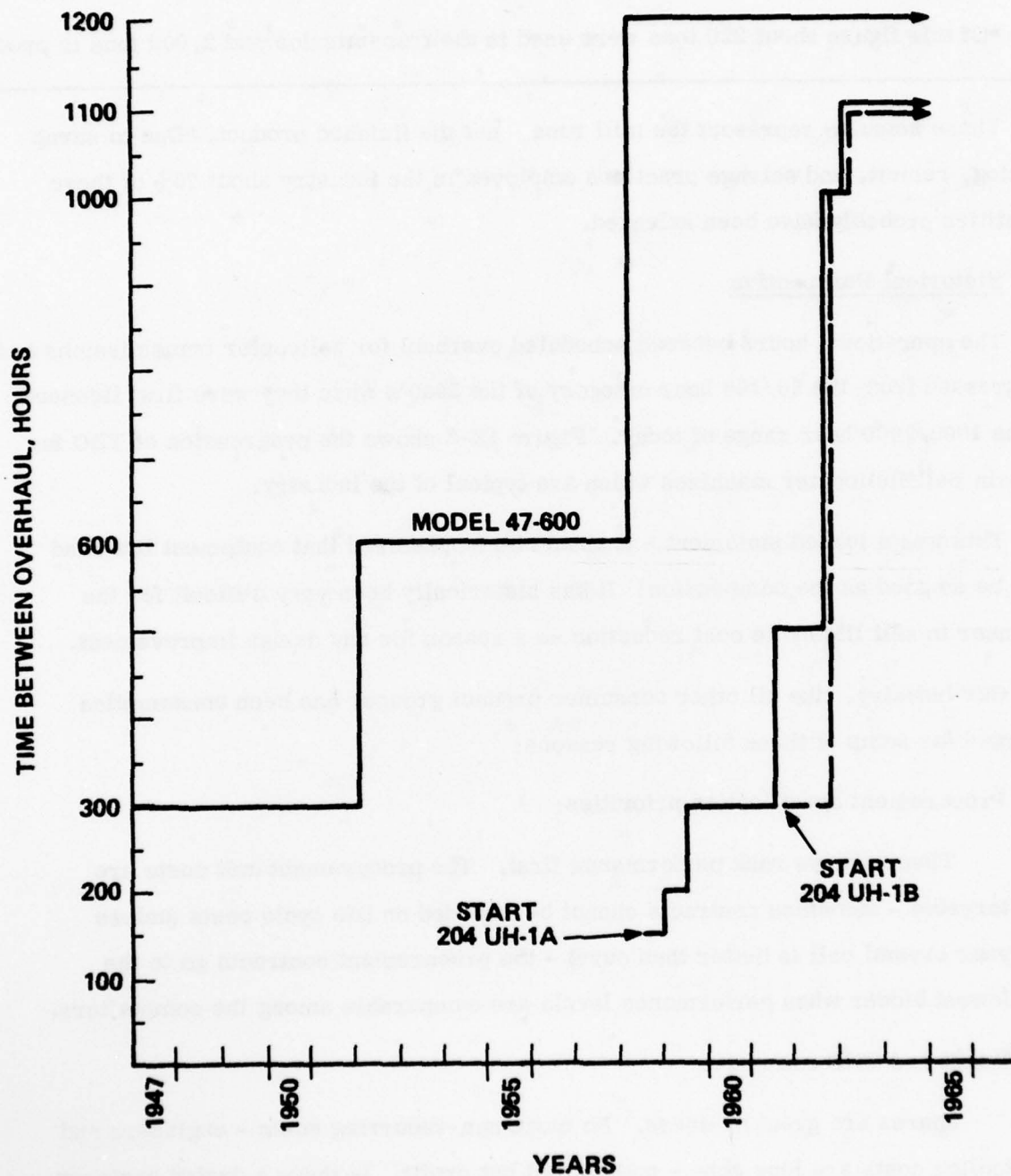


Figure IX-3. TBO vs. Calendar Year

- **Lazy design and clichés:**

How many times has an unnecessarily expensive material or process been used in the interest of expediency or insufficient engineering time available to take a hard look? That's not aircraft quality! The customer likes M-50! We've been doing it that way for years - no need to change now! Ad infinitum.

- **Standing facilities:**

What on earth would become of the NARF's and Depots of the World? CCAD, San Diego, Panama City, -- employ thousands of civil servants dedicated to the salvage and refurbishment of the Government's equipment. What would they have to do if component lives were doubled?

- c. **Potential Wear Life Increases**

Significant MTBR increases were shown to be life cycle cost effective and feasible, within the present state of the art in USAAMRDL TR 72-40. Operational helicopters of the 1980's and 90's are expected to demonstrate double the MTBR lives of those in operation today.

However, the full potential of MTBR increase savings will never be reached until on-condition maintenance replaces the TBO cycle. This cannot happen until reliable diagnostics and prognosis systems are developed and drive systems are shown to have only kindly failure modes.

The secondary benefits of wear life increase are enumerable. Among these are bringing maintenance cost/flight hour down to levels competitive with other forms of transportation.

1. **How is life cycle costing now used?**

For the most part it is now simply "lip service." Finding basically rational scenarios and life cycle models which retain sufficient flexibility to assure their applicability through the next decade is a difficult task. Historical records exist which enable good cycle costing of the 1962 - 1974 RVN experience - but far different results are found for similar reviews of commercial experience.

Some life cycle cost results at two MTBR levels based upon data taken from Figures IX-4 and IX-5 are:

<u>HYPOTHETICAL - UH-1 - CASES</u>		<u>COST IN \$/HR.</u>
a) MTBR	950*	1630**
b) Overhaul Costs	3.00	1.74
c) Downtime Cost at 3.50/hour at 16 hours	5.89	3.43
d) Capitalization Costs (useful life - 8,000 hours)	<u>1.88</u>	<u>1.88</u>
e) Life Cycle Costs	10.77	7.05

$$\Delta \text{Cost} = \$3.72/\text{hr.}$$

Net savings potential, RVN, 800,000 hours/year late 1900's.

$$\Delta \text{Cost} = 2.9 \times 10^6 \text{ Dollars/year}$$

*UH-1 experience, ref. USAAVLABS TR 70-66.

**205A-1 commercial potential/experience - circa 1970.

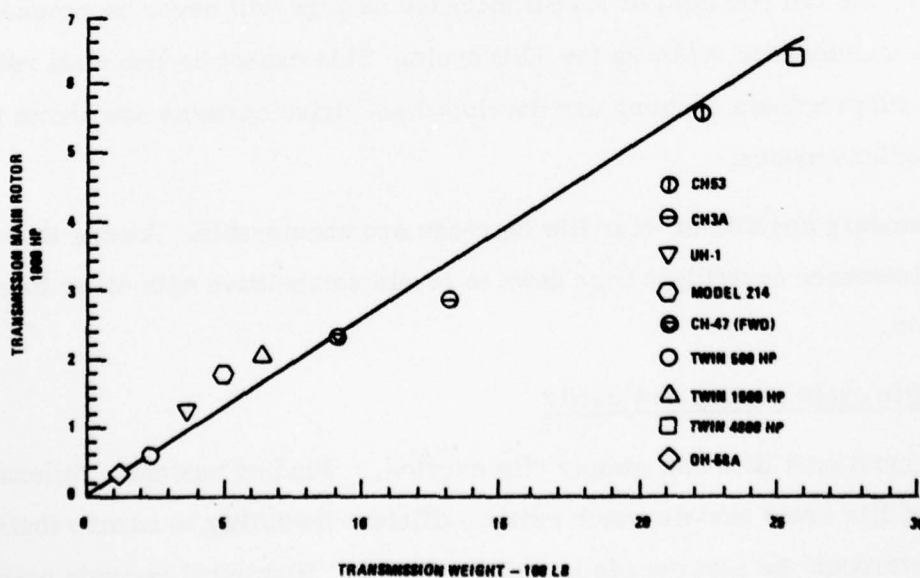


Figure IX-4. Transmission Weight Vs. Horsepower

Transmission	Turn-around OH Cost (\$)	Transportation RVN Round Trip (\$)	OH Period (hr)	MTBR (hr)	Cost * (\$/flt hr)
UH-1	2300	610	1100	995	2.93
CH-47B Aft	6362	1410	600	523	14.80
CH-47B Fwd	5909	1530 (Avg)	600	449	16.60
CH-47B Comb	6478	620	1200	1189	5.95
CH3A	9100	2080	850	345	32.30
CH3C	9100	2080	500	286	38.90
CH53	15505	3655	500	204	94.00

$$*Cost/Flt Hr = \frac{(OH + Transport)}{MTBR}$$

Ref. USAAMRDL TR 72-40

Figure IX-5. Overhaul Cost Breakdown

Cost effective implementation of wear control.

Significant advances depend upon active support in these minimum areas:

- Real industry incentives (In part dependent upon financial rewards which can only be effected on long range budget-control programs, something the Government is now unable to do.)
- Breakthroughs in on-condition maintenance capability.
- Evolution of an economic system whose cornerstone is not consumption.
- Research and development programs oriented toward understanding design techniques and materials for extended wear life.
- Special emphasis on system development to extend corrosion life of transmission materials - for this now exists as a "brick wall" barrier at roughly 2X present MTBR levels.

2. "Helicopter Drive Systems" by A. J. Lemanski

a. Helicopter Transmissions

The reliability state-of-the-art of helicopter transmissions is shown on Figure IX-6 which plots MTBR (Mean Time Between Removal) against the cumulative experience of the transmission. The reliability status of current technology design is shown both with and without the present policy of fixed time removals (TBO's) and with more extensive development programs. Upper limits for current and advanced technology are suggested. To provide an approximation of the actual impact of these various MTBR levels the number of removals and cost per year are shown corresponding to the MTBR scale. Assumptions used in this quantification are shown.

The nature of the reliability level at the point indicated on Figure IX-6 is examined further in subsequent discussions.

b. Current Status

The present experience of helicopter main transmissions (representing current technology) is shown on Figure IX-7. A 900 hour MTBR for both scheduled and unscheduled reasons is the overall average with TBO intervals of 1100 to 2000 hours. The unscheduled removals only resolve to a MTBUR of approximately 2000 hours.

Transmission designs currently under development are intended to operate without a TBO (on-condition). With this situation the MTBR should be close to the MTBUR. Thus, the MTBUR of 2000 hours is considered the baseline reliability and is examined in more detail in Figure IX-8.

Three groups of unscheduled removals are examined. The inherent failures constitute approximately 60% of the unscheduled removals. The remaining removals are equally split between those units removed through false indication of failure, inadequate diagnosis, or erroneous troubleshooting which do not have an actual functional discrepancy and those which are removed due to real damage or suspected damage incurred because of a maintenance or operational action. The removals that could be addressed through basic design or technology are indicated.

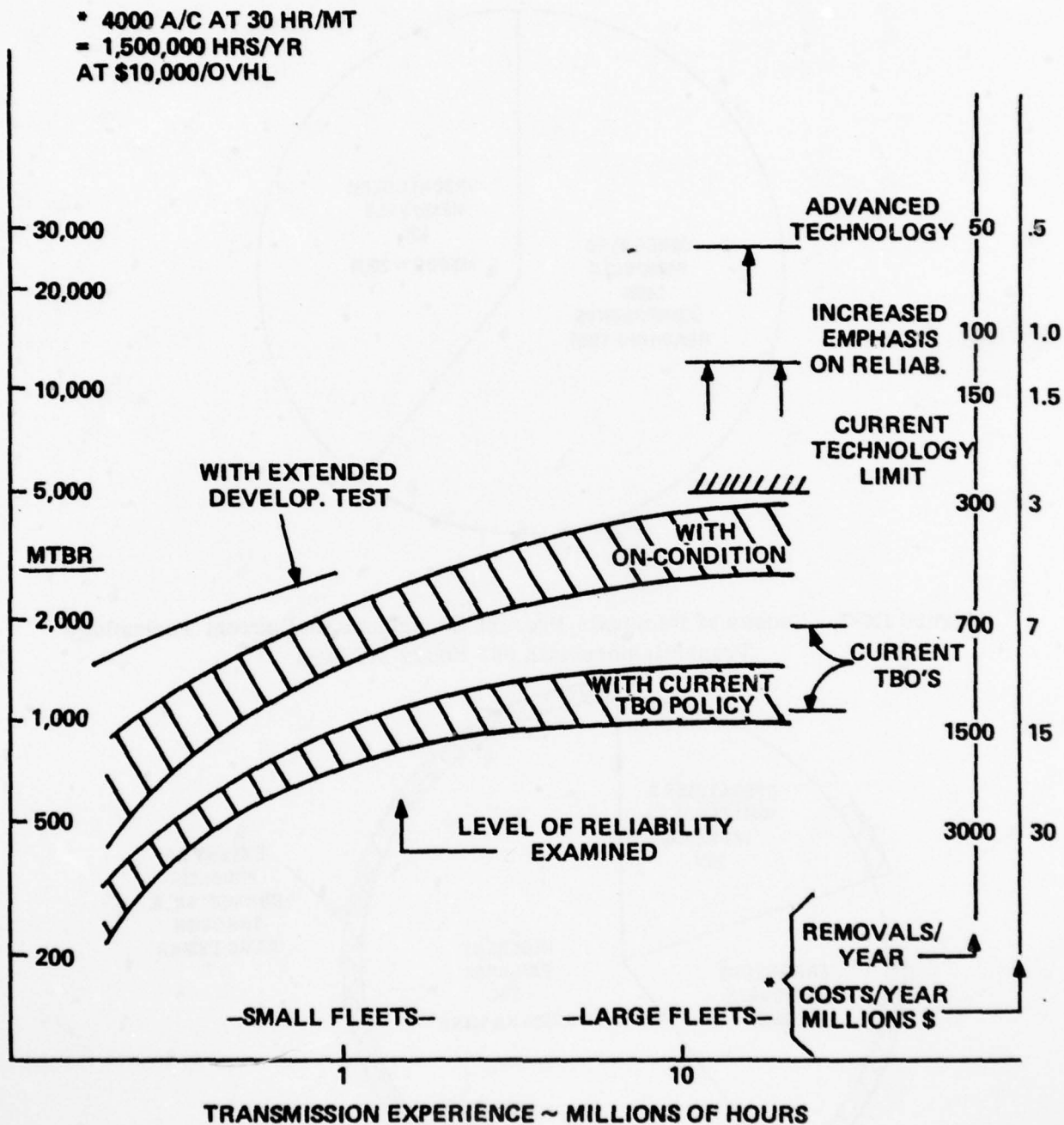


Figure LX-6. Helicopter Transmission Reliability State-of-the-Art

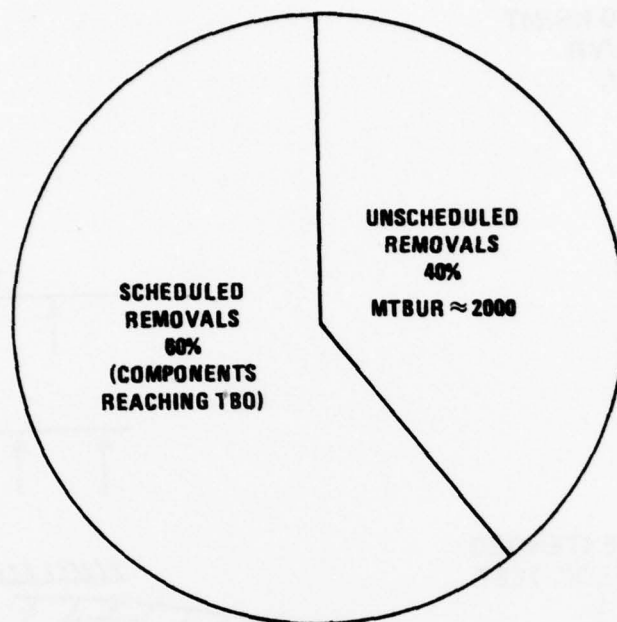


Figure IX-7. Causes of Removals Present Experience on Current Technology Transmissions with 900 Hours MTBR's

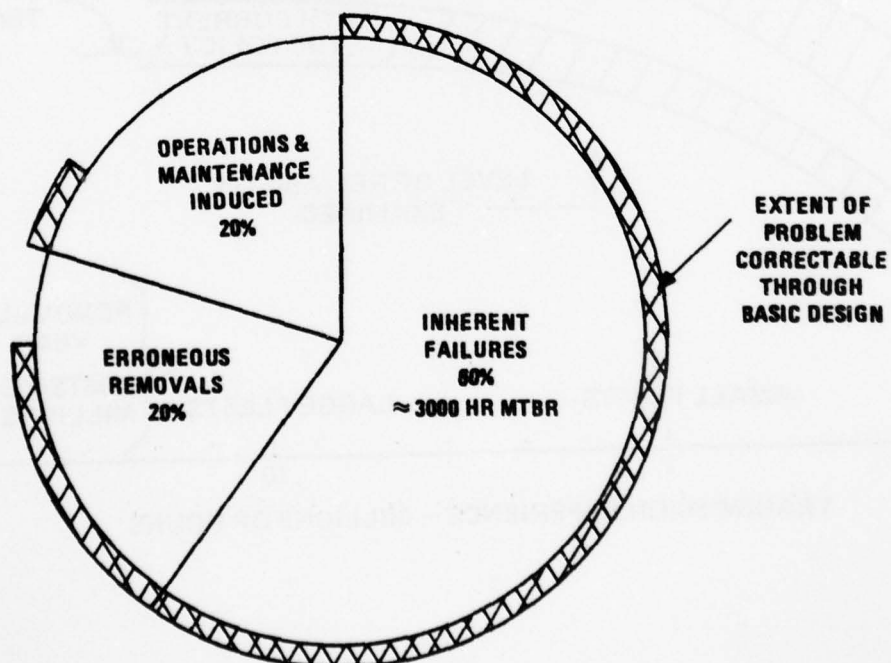


Figure IX-8. Causes of Unscheduled Removals of Current Technology On-Condition Transmissions with 2000 Hour MTBR's

Each of these groups is examined further. The inherent failure causing removals is shown in Figure IX-9 allocated to the primary component which failed.

Erroneous removals, however, by their very nature cannot be assigned to components. The field reported symptoms, however, do provide a clue as to the nature of the erroneous removal problem. This distribution for CH-47 transmission only is shown in Figure IX-10.

This display suggests that the majority of erroneous removals may be related to some problem or unusual condition within the assembly. The reason they were considered erroneous is usually that the criteria for removal was misinterpreted by maintenance personnel. Thus, improvements in the basic reliability of the design can address a portion of these so-called erroneous removals. Furthermore, the components causing inherent failures may be contributing to these erroneous removals in a similar proportion as that shown on Figure IX-9. Of equal potential as the improvement in basic reliability is the benefit that improved diagnostic systems could have on reducing the frequency of erroneous removals. The improved application

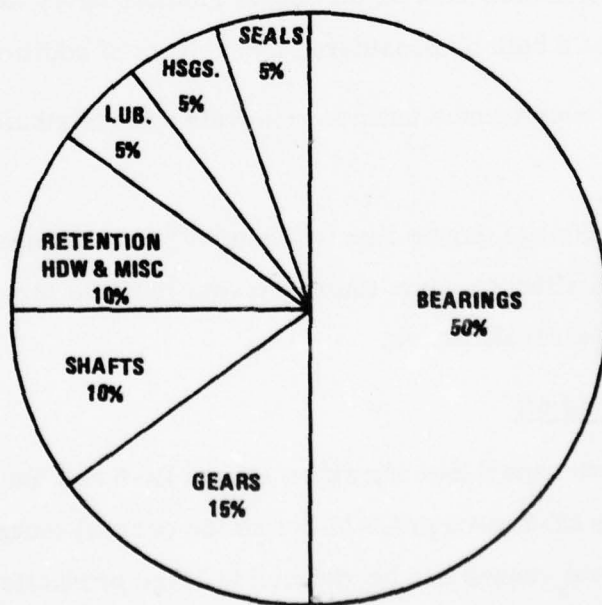


Figure IX-9. Component Contribution to Inherent Failures Causing Removals

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PROCEEDINGS OF A WORKSHOP ON WEAR CONTROL TO ACHIEVE PRODUCT DU--ETC(U)
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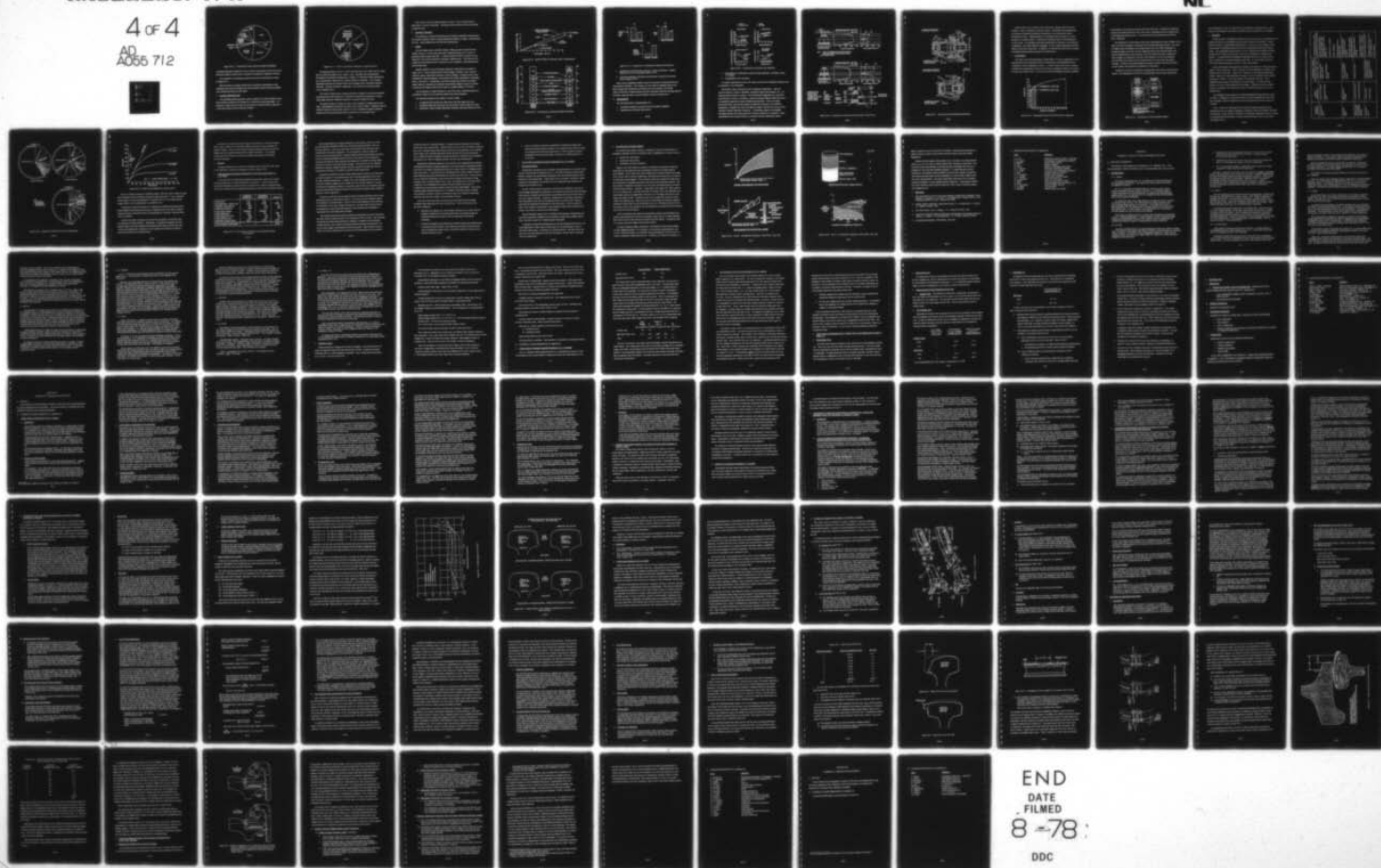
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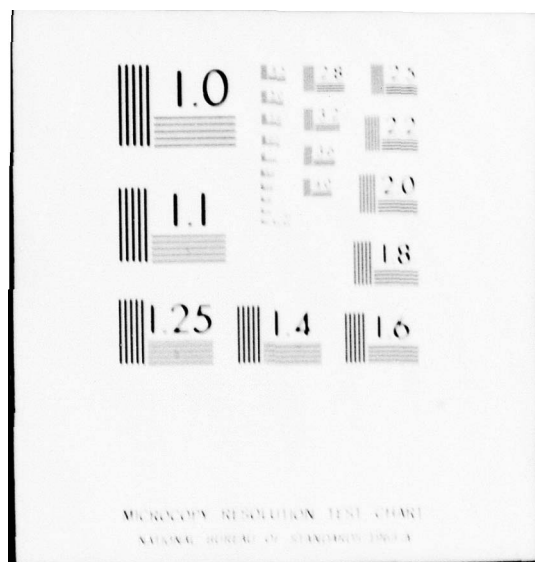
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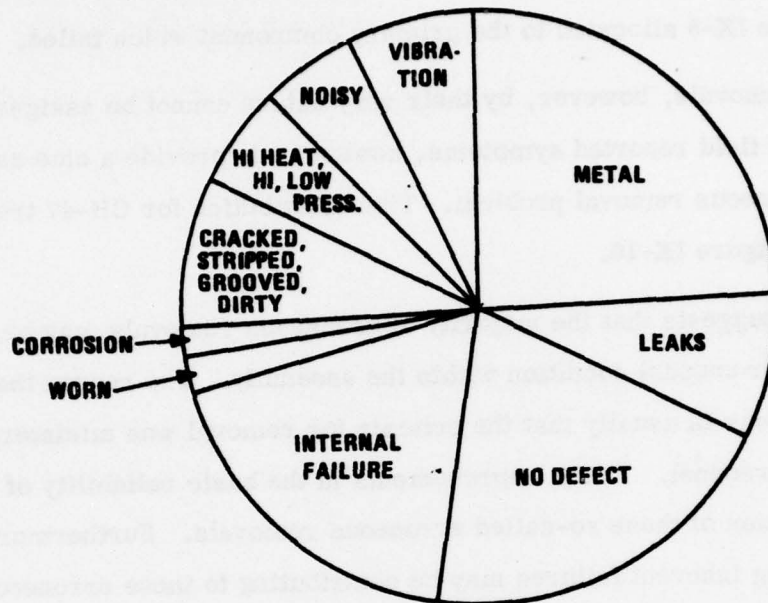


Figure IX-10. Transmission False Removal Symptom Distribution

of existing diagnostic techniques such as oil debris monitoring as well as the use of advanced techniques should both be considered as subjects of additional research.

The operations and maintenance induced removals are distributed as shown in Figure IX-11.

Only the portion of damage during removal can/will be addressed by basic reliability improvements although some improvements could be directed profitably at the damage during on-aircraft repair.

c. Current Technology Limit

The reliability growth experience shown on Figure IX-6 and the detailed causal factors shown in Figures IX-7 through IX-11 define the current technology. The frequency of these removal causes can be reduced in large production programs to a level that produces 3000 to 6000 hour MTBR's.

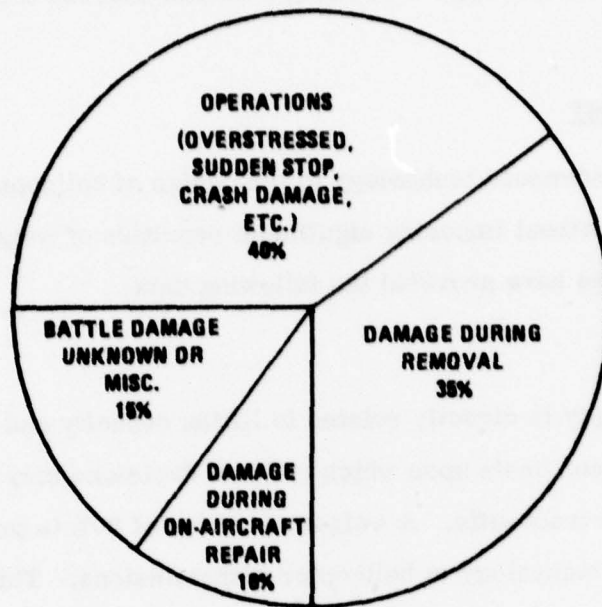


Figure IX-11. Types of Operations/Maintenance Caused Removals

An integral element, however, of this technology limit is the subtle but real trades that are performed between size, weight, costs, reliability and maintainability. Particularly in helicopter transmissions, weight is an important design consideration and, unfortunately, frequently has a negative effect on reliability. Use of certain lightweight materials and sizing of gears and bearings produce operating conditions (stresses, corrosion resistance, alignments, etc.) which can be directly related to this reliability level.

The results of these types of design trades form a pattern on nearly all helicopter transmissions and may therefore be considered an inevitable consequence of rotary wing design within the traditional emphasis on minimum weight and costs.

The specific impact on weight and costs as this emphasis is shifted toward reliability, maintainability and general durability is not clearly evident. Additional research should be directed at this specific subject in order to identify the highest reliability possible with current technology within reasonable costs and weight limits.

Most of these costs and weight penalties, however, can be avoided with the application of advanced technology. Following sections address these advancements in general terms.

d. Advanced Technology

The application of advanced technology to the design of helicopter transmissions will benefit reliability without imposing significant penalties of weight, maintainability and cost. Recent studies have provided the following data:

1. Weight

Aircraft weight empty is directly related to lifting capacity and performance. Weight provides a common basis upon which rational decisions may be made regarding potential design trade-offs. A weight reduction of 20% is projected for the application of advanced technology to helicopter transmissions. This will provide a margin for trade-offs that may be required to reach reliability, maintainability and producibility goals.

Specific weights for several existing helicopter transmissions are plotted in Figure IX-12. These weights include cases/housings, bearings, seals, spacers, retainers, gears, planet gear assembly, internal shafting, accessory drives, free-wheeling unit, gearbox supports, and complete lube system (including oil, plumbing, blower, and cooler). Considering a mean line through these points, the specific weight trend for contemporary helicopter transmission designs is about 0.40 lb/hp. A projected 20% weight reduction will result in a specific weight of 0.32 lb/hp.

The percentages of weight attributed to each of the major component groups are presented in Figure IX-13 for both the baseline and advanced system.

The following techniques were applied to reduce weight:

- Arrangement that shortens the high torque load path (Figure IX-14A).
- Simplified design that minimizes size and number of parts (Figure IX-14B).
- Application of high strength-lightweight composite materials (Figure IX-14C).

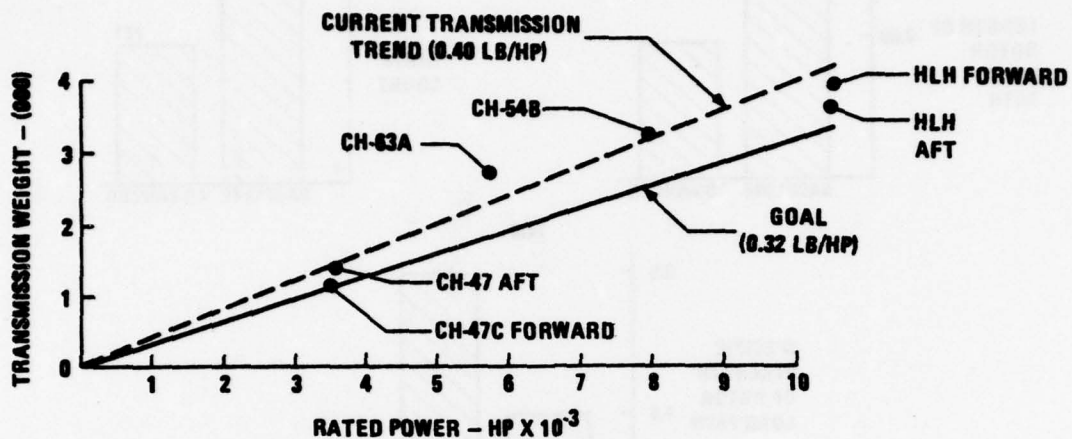


Figure IX-12. Specific Weight of Helicopter Main Transmissions

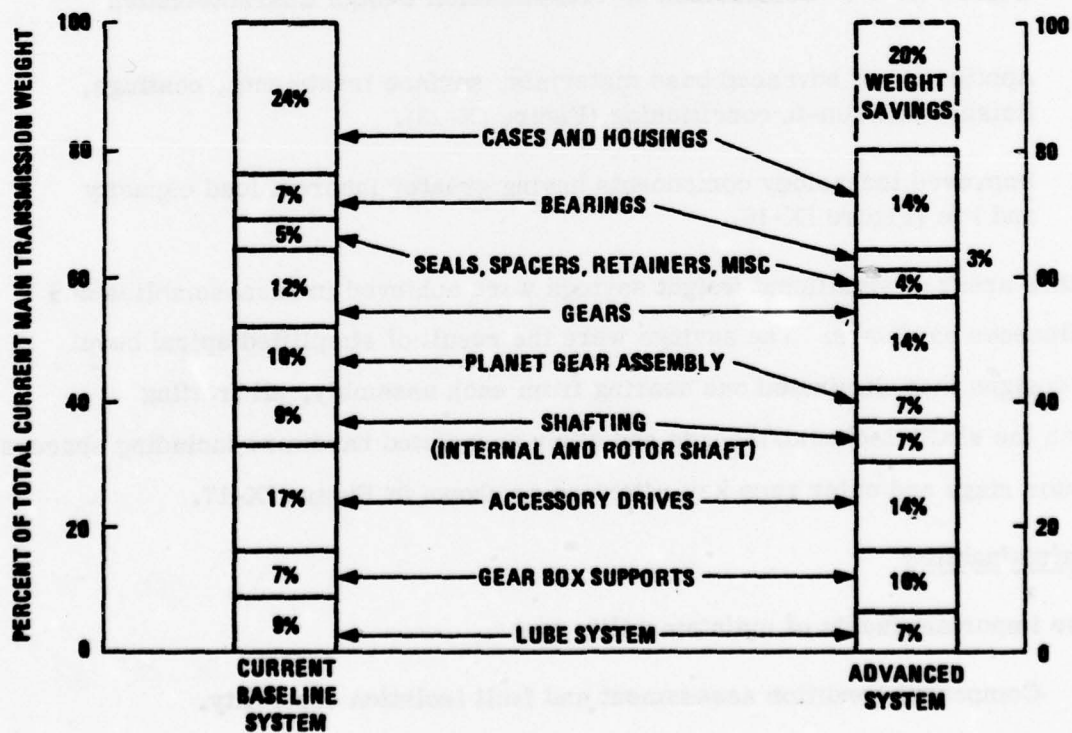


Figure IX-13. Transmission Component Weight Comparison

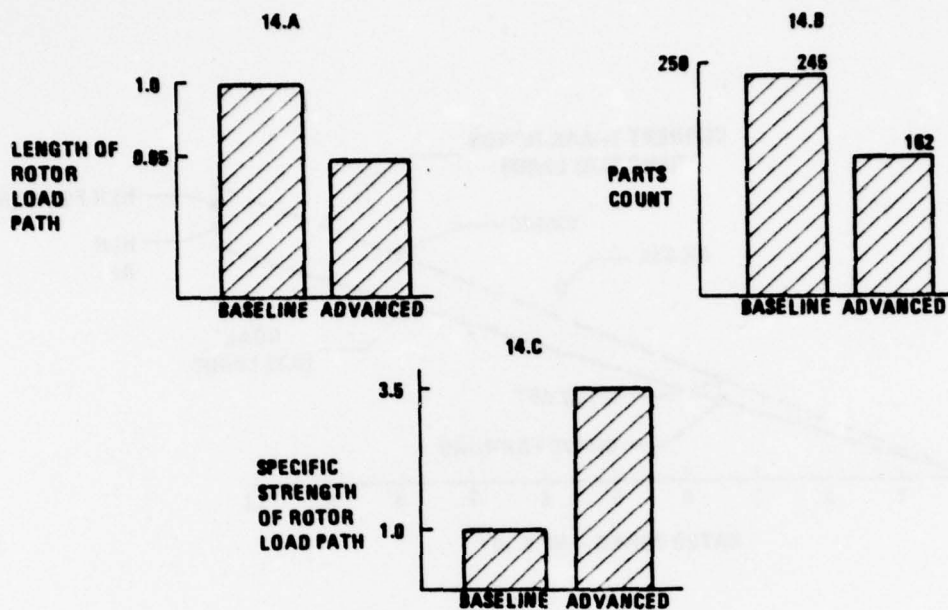


Figure IX-14. Comparison of Transmission Design Characteristics

- Application of advanced base materials, surface treatments, coatings, finishes and run-in conditioning (Figure IX-15).
- Improved technology components having greater inherent load capacity and life (Figure IX-16).

Other areas of significant weight savings were achieved in subassemblies and miscellaneous hardware. The savings were the result of simplified spiral bevel pinion designs that eliminated one bearing from each assembly, all fretting joints on the shaft, locknuts/threads and other associated hardware including spacers, lubricator rings and outer race key retention as shown in Figure IX-17.

2. Maintainability

The important facets of maintainability are:

- Component condition assessment and fault isolation capability.
- Inspection and servicing requirements.

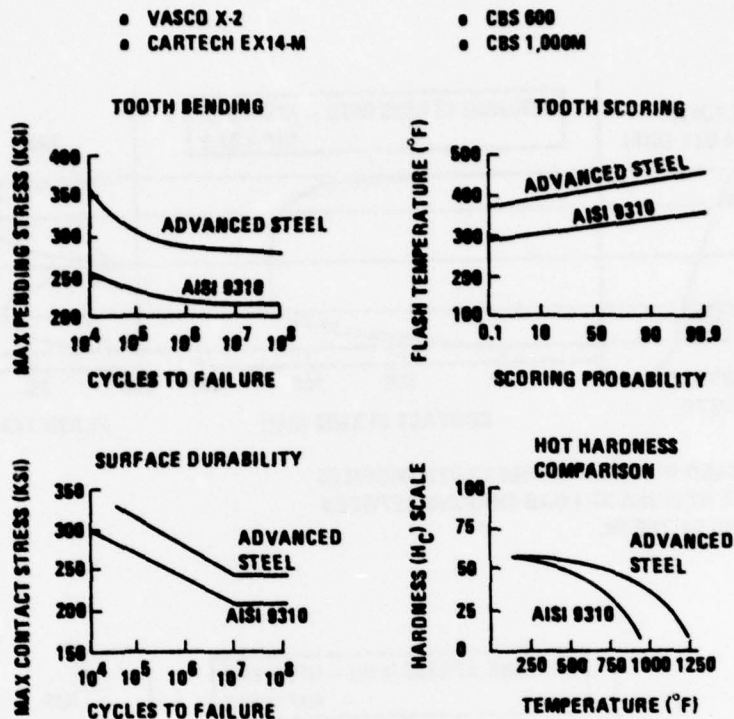
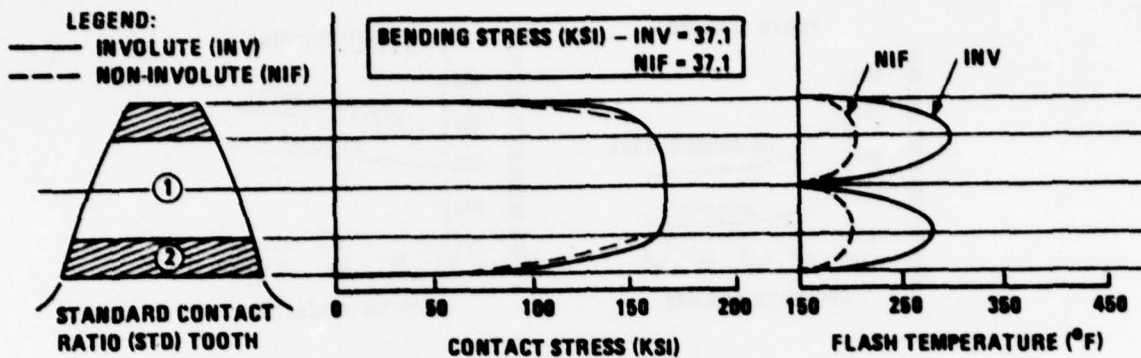


Figure IX-15. Comparison of Advanced Gear Materials

- Susceptibility to maintenance damage during installation, servicing, repair, or overhaul.
- Accessibility to the component.

To achieve improvement in this area, false removals and maintenance damage must be minimized, if not eliminated.

Historically, many removals are due to inadequate diagnostics. Units are removed because of noises, vibrations, suspected unusual temperatures, etc., all using extremely subjective criteria. Even the standard diagnostic tool, oil debris (chip detectors, screens, and filters), requires personal judgment which often leads to assemblies being found in good condition upon teardown. There are design approaches which can make the design and diagnostics interface more effective. Specifically, simplified and stiffer housings and support structure can aid any of the vibration-oriented diagnostic techniques. A completely integral and simplified lubrication system also allows improved oil debris methods to be employed. These requirements can be incorporated in an advanced concept transmission system



NOTE: ENCIRCLED NUMBERS WITHIN TOOTH PROFILES
 DENOTE REGIONS OF LOAD SHARING BETWEEN
 1, 2 OR 3 PAIRS OF TEETH.

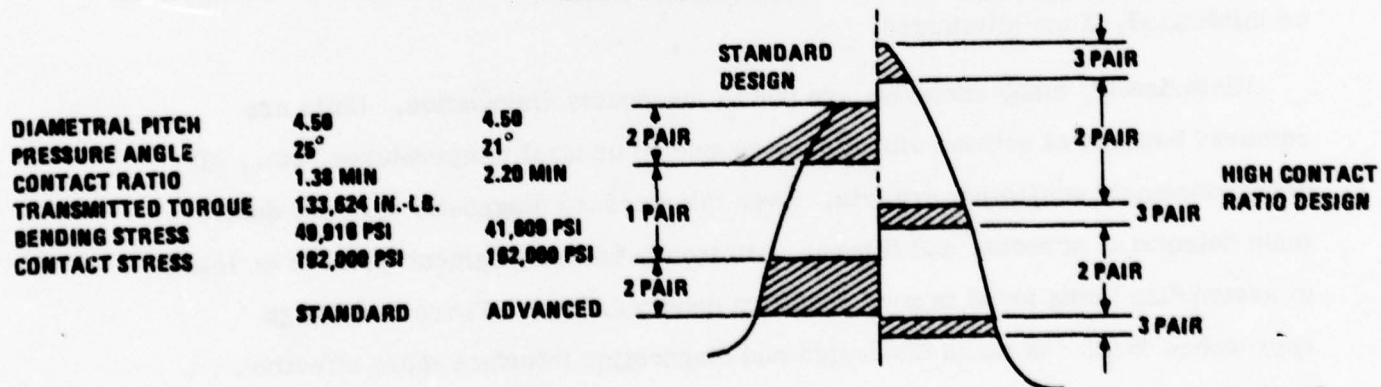
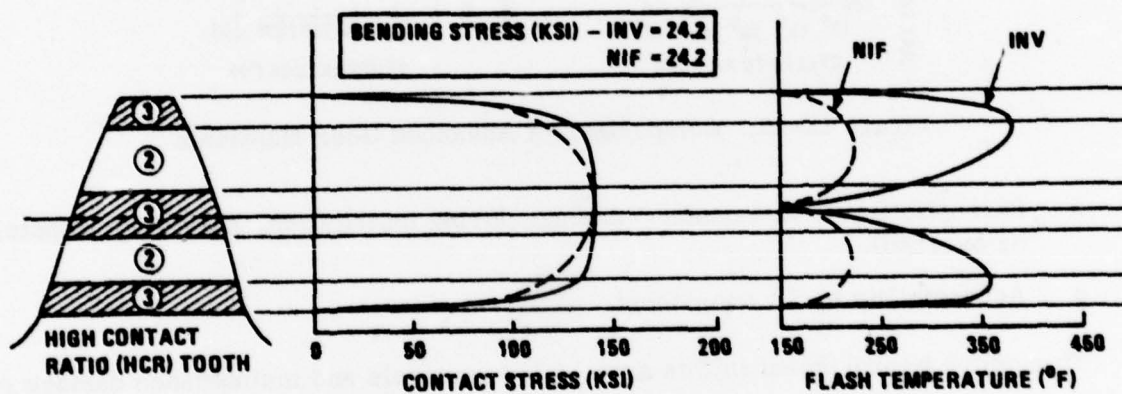
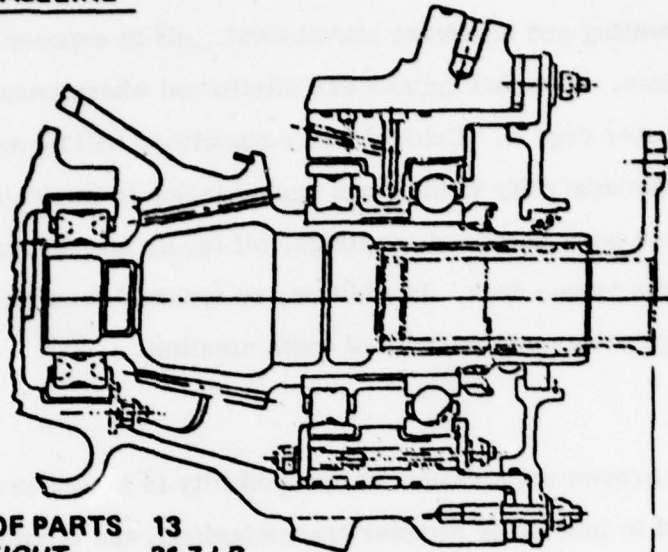


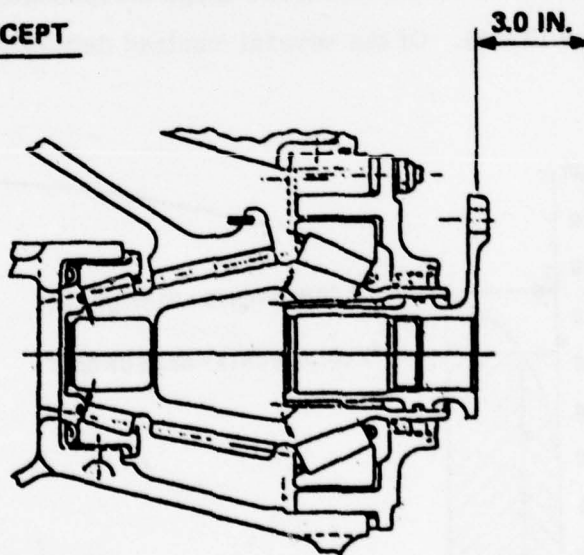
Figure IX-16. Comparison of Involute and Non-Involute Tooth Forms

CURRENT BASELINE



NUMBER OF PARTS 13
TOTAL WEIGHT 21.7 LB

ADVANCED CONCEPT



NUMBER OF PARTS 7
TOTAL WEIGHT 14.8 LB

Figure IX-17. Spiral Bevel Pinion/Bearing Comparison

Another major area of concern is the maintenance damage suffered by transmissions. This is manifested in external splines, connections to the housing (both for structural mounting and hardware attachment), and in exposed lubrication distribution systems. External splines are eliminated where possible or at least protected to a greater degree. Critical bolt connections will be self-indicating for correct torque. Accessibility to the main transmission is improved by the proposed arrangement, since input shaft and couplings, oil level, and all inspection/servicing points are above the torque deck. In addition, no external lube lines will be required, eliminating leakage points and sources of contamination.

3. Producibility

The major improvement foreseen in producibility is in new arrangements of components which lead to inherently simpler transmissions, the elimination of some components, and the integration of others. A review of piece part costs in a typical contemporary transmission shows that a few large components account for the bulk of the costs (see Figure IX-18). Of the several hundred defineable parts that constitute

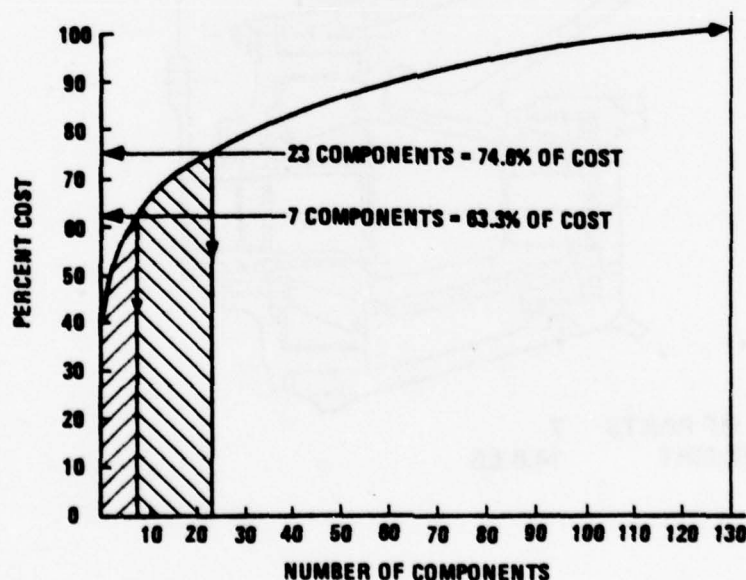


Figure IX-18. Transmission Cost is Driven by Major Components

this assembly, seven alone account for 63% of the total cost. Evidently for significant saving in recurring production costs, these major components must have high priority in the design innovation process. An advanced-concept transmission must address these components.

The distribution of costs within a main rotor transmission is shown in Figure IX-19, where the 1960-era design is compared to the advanced technology concept. The areas of change include elimination of the shaft portion of the rotor shaft, integration of housing and upper cover into one unit, integral bearing races with gear shafts, and general simplifications in the assembly as a direct result of the new arrangement. These changes are estimated to provide a 20% reduction in cost of the assembly, even allowing for increased costs in certain areas such as the rotor hub support bearings. A further and equally significant savings is expected when the total effect of rotor system and transmission integration is considered.

In addition to the basic advantages of arrangement, other areas of improvement include: Full integration of the lube oil cooling system into the main transmission

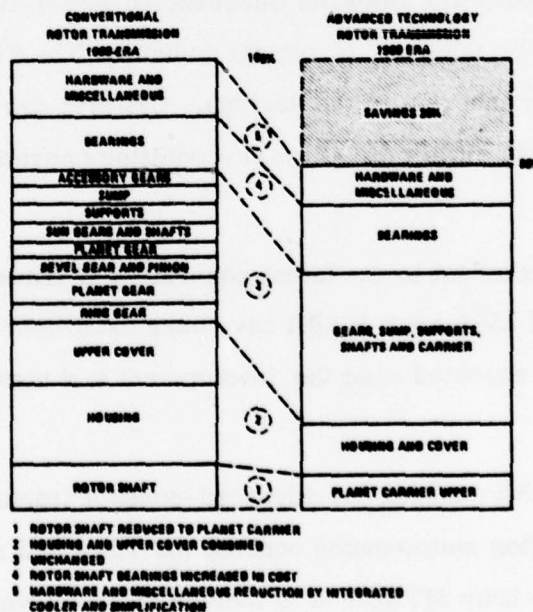


Figure IX-19. Comparison of Costs (Constant Dollars)

thus eliminating oil lines and connections and elimination of bearing locknuts, shaft threads, and locking devices whenever possible through simplified gear mountings.

4. Reliability

A large majority of reliability problems arise from the past lack of precision in our analytical methods for predicting the actual loads and material properties. These problems require a concentrated technical effort. Table IX-2 gives examples of the various kinds of reliability problems with the corresponding improvement requirements. The contribution of these factors to CH-47 transmission reliability is shown in Figure IX-20, where the reason for removals is segregated into categories of failures. It is apparent that the problems originating solely from conscious trade-offs of reliability are a small percentage of the total. It is also apparent that the TBO limit caused unnecessary removal of many transmissions.

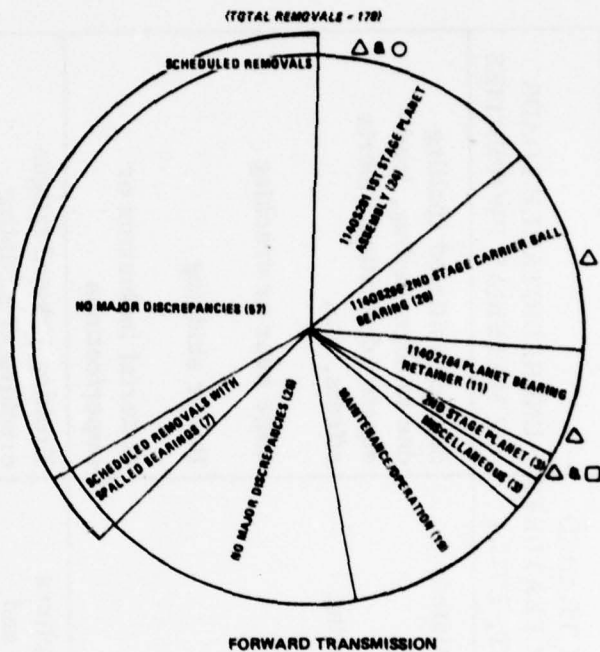
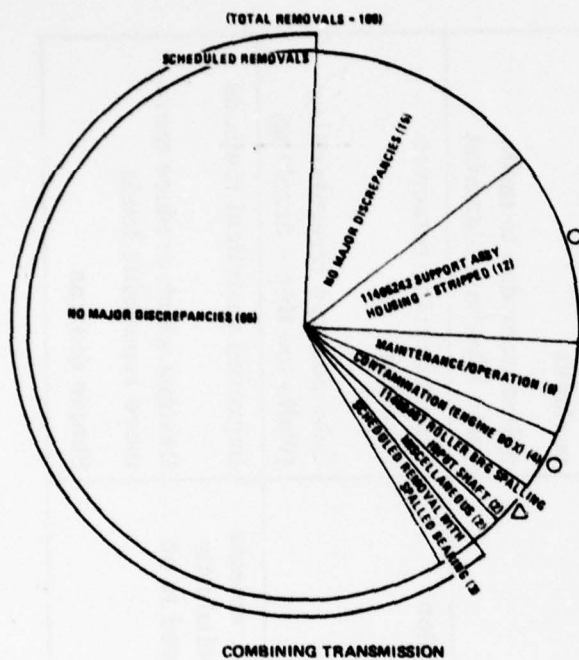
Nearly all helicopter transmissions currently in operation have TBO levels in the range of 1000 to 1500 hours. Thus, regardless of their reliability, the MTBR's are limited to 900 to 1300 hours. Figure IX-21 shows how a TBO interval limits total MTBR. Figure IX-21 also illustrates the range of current reliability levels (usually expressed as MTBUR - Mean Time Between Unscheduled Removals). These reliability levels appear to be inherent to current designs. The TBO intervals, however, are not as clearly inherent to the designs. Criteria are being developed, however, to establish TBO intervals (or allow on-condition operation) on a more rational basis.

The reliability levels inherent to the latest generation of transmissions are not yet known. Design goals of 1500-hour MTBR have been established for these units, and even higher values are expected once the development and maturity cycles are complete.

Thus, a 6000-hour MTBR goal for the advanced-concept transmission goal translates into an on-condition maintenance concept (no TBO) and reliability (MTBUR) of 6000 hours. If this 6000-hour MTBUR is to include all unscheduled removal clauses, it is apparent that the frequency of actual component failures must be very small (see Figure IX-20).

TABLE IX-2. TYPES OF TRANSMISSION RELIABILITY PROBLEMS

TYPES OF PROBLEMS	DESIGN EXECUTION	RELIABILITY TRADED OFF FOR OTHER FEATURES (WEIGHT, COST, ETC.)	UNPREDICTABLE LOADS OR MATERIAL PROPERTIES
Bearings and Gears	Outer race rotation Bearing race spacer wear	Subsurface initiated fatigue spalling Gear tooth bending failures	Surface initiated spalling due to edge loading, inadequate lubrication, debris effects, etc. Cage wear or cracking Roller skidding Material inclusions or imperfections
Shafts and Splines	Spline External damage	Wear or soft splines not carburized and ground	Fretting induced fatigue cracking of mounting surfaces Spline wear due to inadequate lube/misalignment
Retention hardware housing, and lubrication systems	Locknuts backing off External case damage	Housing corrosion	Planet bearing retainers cracking Lube passage irregularities (Walls too thin - cracking)
Corrective action	Design criteria Simple designs	Customer requirements emphasizing reliability trade issues need to be quantifiable	Improved analytical methods Designs which produce more repeatable loads Simple designs



LEGEND:

- = DESIGN EXECUTION
- = RELIABILITY TRADEOFF - ACTUAL POWER LIMIT
- △ = LOADS AND/OR MATERIAL PROPERTIES UNANTICIPATED

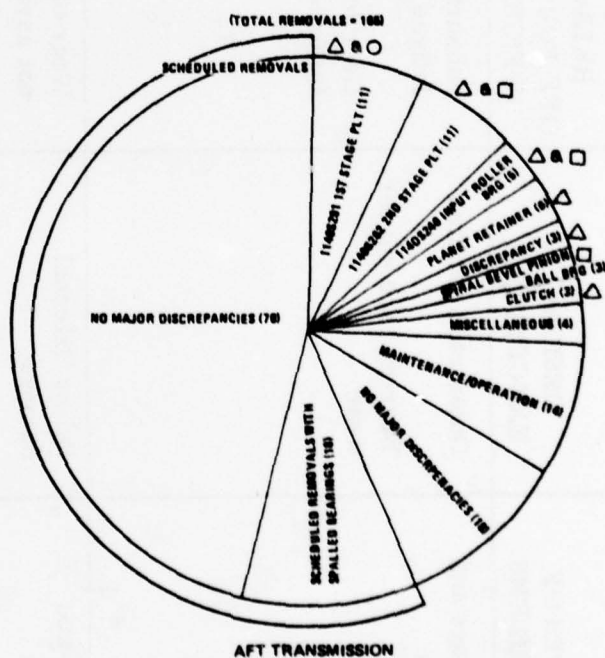


Figure IX-20. Reasons for Removal of CH-47 Transmissions

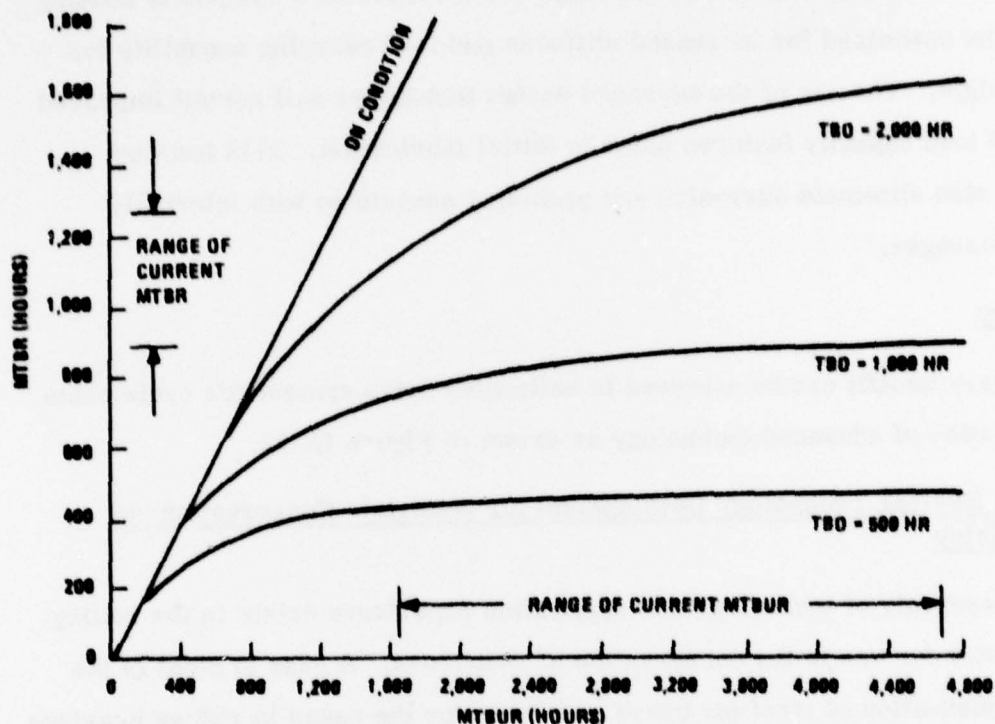


Figure IX-21. MTBR Versus MTBUR for Various TBO's

Based on extensive analysis of reliability history, this will require design concepts which eliminate potential problems through two basic approaches. First, simplicity of the design to avoid the opportunities for analytical errors or oversights during design and also avoid manufacturing or assembly errors.

An advanced concept transmission can incorporate simplified input spiral bevel pinion designs that eliminate one bearing, all fretting joints on the shaft, locknuts/threads and other associated hardware including spacers, lubricator rings and outer race key retention.

Second, the design concepts must decrease the variability of loads that cause the majority of current problems. Specifically, a design that possesses case and internal support structure stiffness significantly greater than currently used could reduce the misalignments, deflections, and resultant load variations and thereby allow achievement of the reliability goals.

An advanced concept transmission design can incorporate a composite housing which could be optimized for increased stiffness and load carrying capability for minimum weight. The use of the advanced design techniques will permit improved stiffness and load capacity features prior to initial fabrication. This housing concept will also eliminate corrosion and problems associated with internally cored lube passages.

e. Summary

A summary benefit can be achieved in helicopter drive system life cycle costs by the application of advanced technology as shown in Figure IX-22.

3. "Rolling Bearing Technology Development for Materials Conservation" by L. B. Sibley

A vast reservoir of technology and application experience exists in the rolling bearing industry for use in the conservation of resources. A case in point is the successful substitution of steel for brass or bronze for the cages in rolling bearings used in the railroad and heavy equipment industries as well as in the aerospace industry.

	CURRENT TECHNOLOGY	ADVANCED TECHNOLOGY	BENEFITS
FLEET SIZE	1,107	1,107	-
ON CONDITION - MEAN LIFE	2,000	6,000	4,000
AIRCRAFT SET COST \$ %	100%	81%	19%
OVERHAUL COST \$ %	100%	81%	19%
CUM FLIGHT HOURS	3,786,420	3,786,420	-
CUM OVERHAULS	1,893	631	1,262
CUM AIRCRAFT SET \$ %	100%	74%	26%
CUM OVERHAUL \$ %	100%	27%	73%
SYSTEM \$ / FLIGHT HOUR	39.00	23.00	16.00
TOTAL BENEFIT (SAVINGS) \$			61.9M

Figure IX-22. Drive System Life Cycle Cost Comparison Details
(1974 Dollars)

The bearing industry is strongly motivated to reduce costs, and it has a clear and demonstrable competitive interest in improving bearing durability, thus conserving materials. In fact, the main thrust of the industry R&D effort has traditionally been to increase bearing life. The development of vacuum melted and vacuum processed bearing steels, improved surface finish and dimensional accuracy, advanced lubrication guidelines (based in part on Navy and Air Force sponsored research) and improved cage materials and designs have resulted in bearing design life factors of three to six times former ratings. These factors are now regularly published in industry catalogs whereas laboratory results have shown that several times these life factors are possible in special bearing applications.

Bearing life prediction has been refined using advanced extreme-value statistics, so that the concept of "zero replacement" life for bearing populations can be used for high reliability applications. A fatigue life model including surface as well as subsurface initiated spalling is now available and was recently expanded to account for lubricant contamination effects in conjunction with the Navy's oil analysis program. Thus the mathematical framework exists for bearing life prediction under conditions typical of service experience.

Greased and sealed for life bearings eliminate bearing maintenance now in many applications such as small electric motors. For severe service conditions beyond the capability of current greases, a POLY-OIL lubricant sponge has been developed. The feasibility of heat pipe cooling of bearings on very high-speed rotors has been demonstrated (in Army sponsored research), thus opening up the possibility of maintenance-free ultra-high-speed bearings.

New bearing material and surface treatment developments can now be visualized that offer almost complete freedom from bearing wear and corrosion. Skin hardening treatments that extend high-temperature capability, sometimes also passivating bearing surfaces, and a variety of advanced powder processed bearing steels, are now in various stages of development toward these goals. Silicon nitride ceramic, which is corrosion-resistant and very hard (Rc 85) and possesses some properties

considered ideal for a bearing material, is being developed intensively for bearings (partly under Navy sponsorship). Silicon nitride has (a) very low dry friction compared steel, thus reducing energy requirements and lost-lube susceptibility, (b) low density (40% of steel), thus reducing high-speed bearing inertial forces and skid tendency, and (c) sufficient fracture toughness (among the highest of ceramics) to give potential bearing life of an order of magnitude greater than the best bearing steels.

Sophisticated statistical techniques now available can be integrated with computer technology and electronic testing equipment for test data analysis and guiding decision processes at all stages of bearing technology from quality control to designing maintenance procedures. A rational basis for specifying critical contact surface characteristics affecting lubrication performance has resulted from this work. In fact, we now foresee having the technology to show that properly designed and operated rolling bearings can be run with virtually "zero" wear, after initial run-in, for their entire design life, thus relegating service failures almost entirely to the realm of accidents from environmental damage (mostly lubricant contaminants). Shock pulse bearing damage detection systems for on-condition monitoring of these accidents early enough to schedule overhaul at convenient times have resulted in substantial materials and resource savings in some industries already.

Just a few of the many ideas on hand now for improving product durability through bearing technology have been reviewed here. These developments fall into three categories:

- Materials and methods now commercially available such as POLY-OIL for stringent maintenance-free bearing applications and bearing design and lubrication analysis in computer codes for application of the latest technology.
- Laboratory feasibility demonstrated new design concepts and materials such as heat pipe cooled bearings, skin treatments and silicon nitride that need only processing and quality control oriented R&D efforts to tailor them for specific application needs.

- Future promising development possibilities in integrated bearing/seal/lubricant/machine structure systems, non-classical surface alloy tailoring, and computer-aided tribology assessments, to open up quantum jumps in maintenance-free product durability, now seen as a definite glimmer on the horizon.

4. "Cost of Wear as Related to Sealing Technology" by L. P. Ludwig

a. Transmission Seals

Leaking seals represent one of the largest replacement items or cause for early removal of gear boxes in helicopters (ref. 1). Seal life is often less than the time between overhauls and considerable maintenance cost and aircraft downtime can be attributed to seal replacement. Leaky seals do not, in general, represent a safety problem; but disassembly and assembly for seal replacement does introduce the probability of assembly error.

The life of seals cannot be predicted, and this can be attributed to the lack of understanding regarding the mechanism (or mechanisms) involved in seal lubrication. Many theories to explain seal lubrication and operation have been put forth (ref. 2), but none is widely accepted. In general, sealing theory is primitive compared to other tribological areas such as bearings and there is a real need for research regarding the fundamental mechanisms of seal lubrication. Once the manner in which a seal operates is understood, then predictive models can be developed and actions can be taken to improve seal performance.

Recent theoretical studies (ref. 3) introduced seal dynamic considerations not previously considered; additional work is needed to bring in heat-transfer effects. Also, this theory needs to be checked against experiment.

It should be stressed that developments in aircraft-sealing technology has very broad application to other areas in which seals are current problems, such as automotive water pumps, and pumps for certain chemicals. The basic ideas also will carry over into elastomeric-lip-seal lubrication, and this field is extremely wide in its application.

b. Gas Path Seals in Turbine Engines

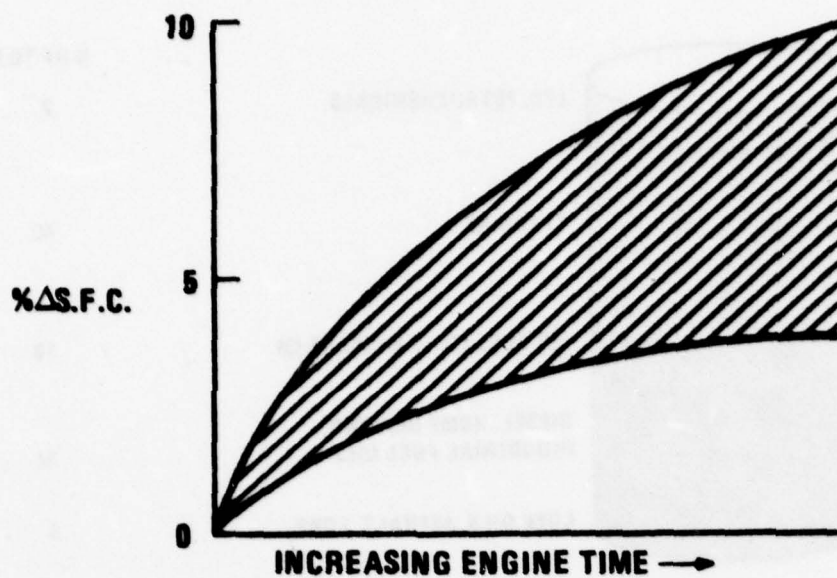
An aircraft turbine engine contains a multiplicity of gas path seals (blade tip, interstage, labyrinth) and the accumulative effect is significant in 3 areas; these are:

- specific fuel consumption
- compressor stall margin
- maintenance of other components

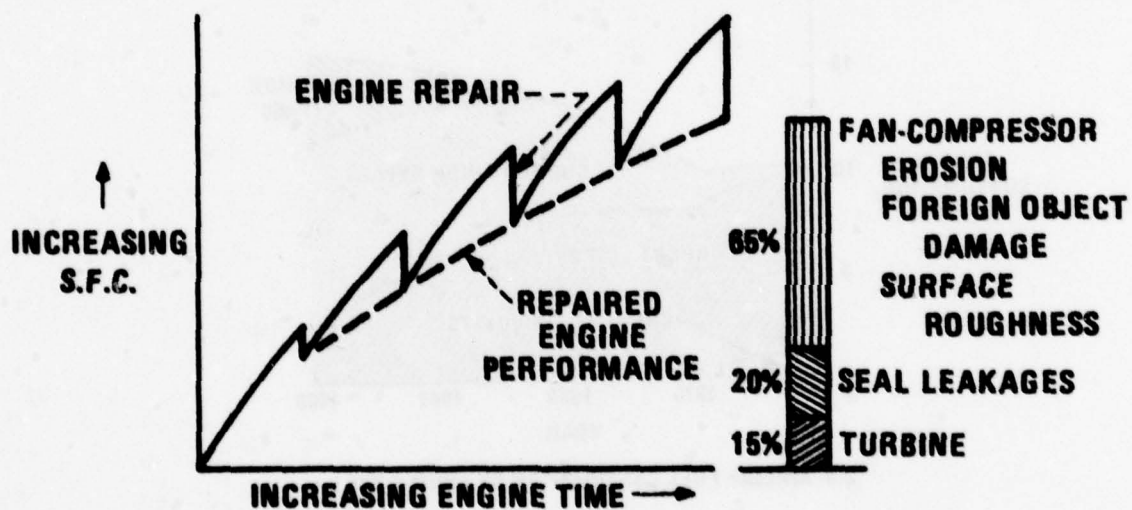
Engines of the 1950 design era operated at relatively low pressure ratios and clearances over the blade tips and at interstage locations were large enough to avoid rubbing. On the other hand, modern engines have pressure ratios in the range of 25:1 and in order to preserve efficiency, the blade tip clearance had to be reduced as compared to early engines. This reduction in blade tip clearances brought about the introduction of abradable materials at the blade tip and interstage location. But this solution of abradable materials has not been fully successful because of erosion and blade wear problems. Typically, a high bypass ratio engine has a SFC increase of 1 to 1-1/2% per year. Periodic overhauls do not fully recover this efficiency loss and the final result is an engine with a SFC that is 3 to 9% higher than that of a new engine (see Figure IX-23). Reference 4 places the average SFC increase at 4% for a fleet of aircraft that has a typical mix of low, intermediate and high time engines. Reference 5 states that the commercial fleet use is 10×10^9 gallons of fuel per year (see Figure IX-24), and, therefore, this 4% degradation represents \$120,000,000/year loss if fuel costs 30¢ per gallon.

Loss of compressor-tip clearance and gas-path erosion adversely affects compressor-stall margin and can lead to compressor surge which is a violent vibration that in turn can have many adverse mechanical and wear effects. Compressor stall is a common reason for engine removal and overhaul.

In regard to general engine maintenance, the integrity of the gas path sealing can have significant effects. For example, as the gas path sealing degrades (due to wear, FOD and erosion), the combustor exit gas temperature must be raised in order to develop the required thrust level. Therefore, the turbine is operating at a

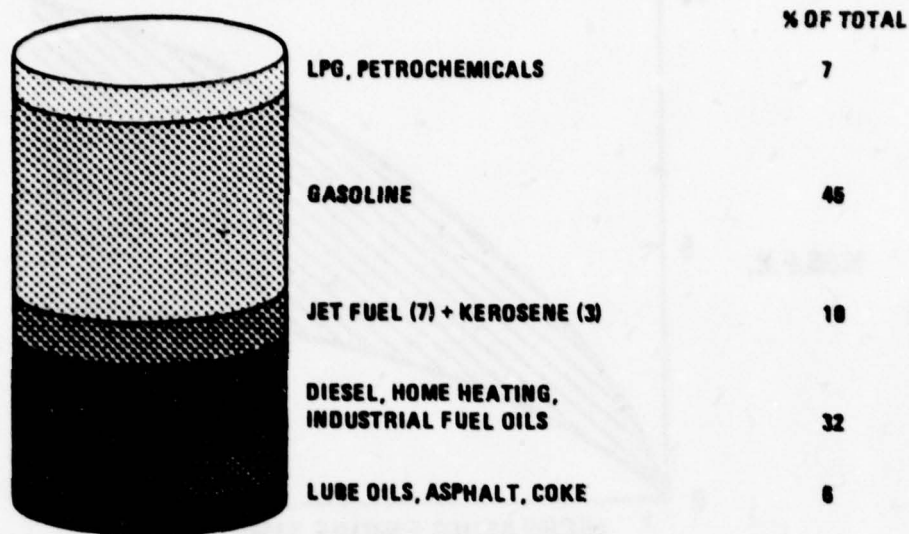


ENGINE PERFORMANCE DETERIORATION

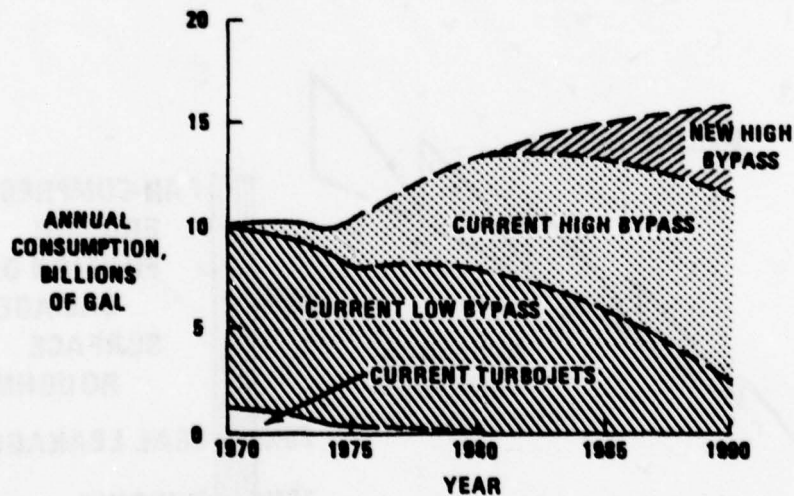


PERFORMANCE DETERIORATION CAUSES

Figure IX-23. Source: Aeronautical Propulsion, NASA SP381, May 1975



DISTRIBUTION OF PETROLEUM TO FINISHED PRODUCTS



U.S. AIRLINE FUEL CONSUMPTION BY ENGINE TYPE

Figure IX-24. Source: Aeronautical Propulsion, NASA SP381, May 1975

higher temperature and its useful life is shortened. High exit-gas temperature is another reason for engine removal that is directly related to gas path sealing degradation.

Advanced aircraft engines will probably have to operate at very high pressure ratios (e.g., 40:1) in order to achieve desired SFC reductions of about 15%. This will place severe requirements on gas-path sealing, and engines will have to be designed for very close seal running clearances. To obtain this goal (of close clearances), the problem must be attacked from two fronts, namely (1) improved rub-tolerant gas-path seals, and (2) minimization of rubs by better control of the case/rotor displacements. This latter requirement requires the use of complex analytical techniques to model engine/airplane integration. Experimental verification of this analytical model must be achieved in order to have an effective design and management tool.

c. References

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3. Face Seal Theory, Part I, Ludwig, L. P., NASA TN-D-8101, 1976.
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5. Aeronautical Propulsion, NASA SP381, May 1975.

C. PARTICIPANTS/INVITEES AT SEMINAR #3

<u>Name</u>	<u>Affiliation</u>
P. M. Ku	Southwest Research Institute - Chairman
C. W. Bowen	Transmission Consultants Incorporated
B. Baldwin	Detroit Diesel Allison
M. Dow	Eastern Airlines
R. Gavert	Office of Technology Assessment
R. L. Johnson	Rensselaer Polytechnic Institute
H. F. Jones	Air Force Aero Propulsion Laboratory
J. Lane	National Academy of Science
A. J. Lemanski	Boeing Vertol Company
L. P. Ludwig	NASA Lewis Research Center
W. A. Mareneck	Mobil Oil Corporation
E. Roeser	Naval Air Development Center
D. Scott	National Engineering Laboratory, U.K.
R. P. Shevchenko	Pratt & Whitney Aircraft
L. B. Sibley	SKF Industries
D. Snediker	Battelle Memorial Institute

CHAPTER X

SEMINAR #4: METAL-CUTTING MACHINERY AND TOOLS

A. MINUTES OF SEMINAR #4

The minutes of the meeting were recorded by Mr. H. Yakowitz, OTA. They were subsequently revised and edited by each of the participants and are given below:

1. Morning Session

V. A. Tipnis:

The cost of machining in the U. S. is estimated to be about \$60 billion by the Machinability Data Center. This figure may range as high as \$75 billion as suggested by Bunshah.

Dr. M. E. Merchant of Cincinnati Milacron, who has recently visited Eastern and Western Europe, points out that the U. S. Government apathy is a major stumbling block to the development of computer aided manufacturing systems in the U. S. He feels that the U. S. is behind the rest of the industrial world in this important technology.

In a typical job shop, only a small portion of machine time (5 to 7 percent) is involved in chip removal. The rest of the time is spent in setting up and also in getting things organized for production. On transfer lines, such as fixed automation, the chip removal time can range from 50 to 60 percent of the total machine time. In CAM systems, it is expected that 70 to 75 percent of the total machine time will be spent in chip removal.

The control of cutting tool wear is crucial to the productivity and leadership of the U. S. manufacturing sector. In this workshop, we hope to discuss specific problems and opportunities involved in the control of wear of cutting tools and machine tools and their impact on manufacturing cost and productivity.

M. K. Gabel:

One Navy production facility can spend thousands of dollars per month for cutting tools. Through the sponsorship of the Naval Air Systems Command under the Analytical Rework Program, a preliminary study investigating coatings for cutting tools was initiated at NADC (see Report No. NADC-74080-30, 11 Sep 1974). Some examples of extended tool life found were:

- a. Bonded film on drill accomplished 100 holes in Ti alloy with no coolant. Uncoated drill with coolant did only two holes. Criteria of failure was burrs around the hole.
- b. Bonded film on taps did 12 holes in one pass, whereas the uncoated did only 2 or 3 holes with two passes on SAE 4340 forged steel.
- c. Ni - W brush plated coating on countersinks made 180 holes in Ti alloy compared to 6 holes made by the uncoated tool.

Therefore, coated tools can reduce man-hours spent in changing, sharpening, storing, and buying tools as well as increase wear life. Additional research may also lead to the reduced usage of coolants and petroleum products. Many nations are interested in this field of development. Rabinowicz (MIT) is studying the compatibility effects involving soft metals as solid lubricants. Japan is investigating the effect of electrostatic cooling and setting up software computer systems for automatic tooling for twist drills, spade drills, boring tools, and lathe work.

E. J. Weller:

New tool materials required added development in application. Most WC and HSS tools are underutilized for various reasons. Most cutting tool failures are breakage and not wear. Need preventive maintenance. Systems analysis for optimum use of tools. Need communications between segments of field. People need education in use of new tools - especially coated tools and ceramics. Speed should mean pieces/unit time, not necessarily higher cutting rpm.

Want closed loop system where fluid is not thrown away. Have run as long as 8 years without disposal. Strip trans. and hydraulic oil from fluid. Similar to dialysis machine for kidney. Need to change lube materials and systems for machine tools and redesign machine tools themselves in order to utilize water base fluids effectively. We need to minimize oil base cutting fluids to save money. Use water soluble fluids - must change tooling to match capability. Water in system is crucial! Use deionized water!

B. F. von Turkovich:

I will limit my comments to the HSS tool spectrum. Current estimate of the industrial type form tools produced in the U. S. A. is (for 1975) of the order of 26×10^6 taps/year and 136×10^6 drills/year.

Although one expects that the major factor in tool life is the conventional wear, we have observed that significant if not the larger portion of taps and drills usually breaks. In order to estimate the tool life, the classical Taylor's plot

should be modified to include a hazard function thus taking into account the unexpected total failure. If the hazard is high, the production strategy should consider the alternatives toward the maximum attainable cutting speed.

When the chipping and fracture of these tools is analyzed, one finds that the yield strength correlates better with the life expectancy than the wear land on similar parameters. The peak hardness (obtained after 2 or 3 tempers) correlates very well with the yield strength.

The ductility is reduced at the peak hardness but in the form tools this is not a handicap.

There is a need for form grinding research, especially for the high hardness HSS tools. Very little effort is currently funded in the U.S.A. in the area of High Speed Steels. The industrial research is stronger and more active in Sweden and Austria, and it appears that the U.S.A. is substantially behind these countries. Very little recovery of HSS tool material is currently anticipated.

C. H. Kahng:

In the United States, more than 3 million tools are currently in operation. In 1975 alone, the value of the machine tools produced exceeded 2.4 billion dollars. For that year, 115,448 machine tools were produced with an average price of \$18,523 per machine.

It is known that the durability of an ideally machined part is much greater than that of an inaccurately machined part. An accurately machined part should have a very fine surface finish with no errors of parallelism, concentricity and roundness. The performance accuracy of the machine tool is responsible for the accuracy and quality of the part and is, therefore, of utmost importance.

If the development of cutting tool materials is reviewed, the operational cutting speeds have increased by two orders of magnitude over the last decade by going from HSS to WC, to ceramic tools. On the other hand, obtainable accuracy or measurable accuracy of machined parts has improved from 10 μ m to 0.01 μ m in the same period.

It is felt that a survey of the grade and accuracy of U.S. made machine tools is necessary for comparison with other industrialized countries, such as the U.S.S.R., West Germany and Japan.

Many research reports indicate that the accuracy of the machine tool (including rigidity) offers many advantages for tool life and surface finish. The surface finish is especially sensitive to the performance accuracy of the machine tool. The effect of temperature and dynamic forces on the total machine tool

structure are also essential. Much more essential is the maintainability of accuracy throughout the life of the machine tool. Therefore, the rotating accuracy of the spindle bearing system through a wide range of speeds, the alignment accuracy of the feed drive system, the guideways system accuracy, and the maintainability of these accuracies should be increased.

The standards for the inspection of machine tools are used commercially by the machine tool manufacturers. These standards, which were established in 1940, are no longer acceptable for automated machine tool manufacturing. Therefore, it is suggested that these standards be revised.

Even though it is said that wear on machine tools is very rare, after a long period of usage, deterioration of the machine tool accuracy is unavoidable. Upgrading the standards of accuracy of the machine tools produced in the United States would minimize errors in the machine parts produced, resulting in improved durability. It is to be especially emphasized that industry and the government should support research for machine tool development to increase accuracy and the durability of this accuracy.

A. Ashburn:

It is important to remember that the goal is the conservation of material, not the reduction of wear. In metalcutting tools, the loss of material from tool wear is negligible compared to waste caused by the production of inferior or scrap parts. Such waste can come either from the use of a machine that has become too deteriorated or from the use of improper tools. Although the waste in this way is probably substantial, there is no real data available. Some years ago the editors of American Machinist estimated the extra cost of machining resulting from the use of obsolete machine tools at more than \$1 billion per year, but this included both scrap material and the extra working time required to make the parts.

In undertaking measures to apply the savings of wear technology to metalcutting machines and tools, therefore, either a total cost of material or a total cost of production, through the entire manufacturing system of a product, must be used as a basis. Which is chosen will depend upon the importance given to the possibility of material shortages.

An example of the direct savings possible is that where a machine is capable of using negative rake tools, twice as many cutting edges are available on each cutting tip as are possible when positive rake tools must be used. A comparison of machine tool world production shows that the U. S. has regained lead in machine tool sales.

R. F. Bunshah:

A. R. C. Westwood of RIAS estimates that rock drilling in the USA costs \$8 billion a year. The time factor to replace worn tools is very significant for deep holes.

Chemical vapor deposition process is currently used to coat carbide tools with TiC, TiN and improve life by a factor of 3 to 10. CVD cannot be used to coat high speed steel tools because the deposition temperature is too high. Recently, Physical Vapor Deposition Techniques using Direct Evaporation in USSR and Activated Reactive Evaporation in USA and Japan have been used to coat carbide and high speed steel tools producing similar improvements in tool life. Since the PVD processes are more versatile than the CVD process, i.e., enable one to deposit various compositions of hard compounds, cermets, etc., one should expect that greater improvements in tool performance of both high speed and carbide tools can be expected. A significant effort is needed to spur this development which is not currently funded at a level commensurate with achieving such performance. In my opinion, an investment of \$1 to 3 million over the next 3 to 5 years is needed to arrive at this goal. It should be pointed out that at just one institute in the USSR, the Paton Welding Institute, there are 150 persons engaged in work on electron beam evaporation of which 15 are working on hard coatings for tools!

R. E. Matt:

Powder Metallurgy is a rapidly advancing method of hardware fabrication which offers the nation considerable savings in time and materials. An estimated 40 to 60% material savings may typically be realized from the ability to produce a part to shape rather than machine it from bar stock. In terms of some of the higher cost materials, i.e., high speed steel costing \$2.00 to \$6.00 per pound, this saving is significant. It is doubly significant when it is coupled with the reduced inventory requirement of machine tools necessary to produce those parts.

In the past, P. M. was associated with small inexpensive hardware. That is not true anymore. P. M. superalloy components are used in most of the new jet turbines like those proposed for the B-1. Stainless steel parts have been produced to shape for a number of years and now high speed steel can be produced to shape and 100% density without working. The problem is recognition.

New processes, no matter how good, are difficult to get across to industry. Frequently data relating to market size, and cost to produce are virtually secrets. Anyone other than an established supplier is held ignorant of what he has to present and consequently has difficulty gaining support. The customer isn't much help either. He usually has the policy - It can't be any good; otherwise, I would have heard of it 10 years ago.

Inventor companies are reluctant to seek help from the normal federal agencies because of potential exposure as public knowledge and the elimination of the government as a source of profit. In addition, the government normally has a product in mind and not a method to reduce the process costs of the product.

The solution to the problem of generating material and dollar saving technology is therefore not what can be done to do it better but how do we get the current better ideas in operation. The generation of a central Industrial Technology Office should be the answer. The agency would not be a funder of basic research nor would it be associated with product oriented centers like the Military. It should work closely with industry and know its needs and costs. Dollars would be required to proof semi-developed ideas. If the process or product is good, the new organization may not be able to guarantee an established market but it will be able to get it a quick unbiased introduction.

J. Galimberti:

Carbide scrap can be recycled and is being done, but it does not end up as carbide tools. Scrap carbide goes to tire studs, hard facing rods, and crushed carbide abrasive surfaces. Scrap carbide ranges in price 50¢ - \$2.50/pound. Range is quantity and quality dependent. Optimum use of carbide as cutting tool - run insert and feed as fast and deep as you can but protect remaining cutting edges. These get damaged by chip erosion and breakage. Most carbides are cobalt binders - but cobalt leaching occurs due to lubricating fluids. But coated tips are better since this leaching is minimized; fluid cannot get at tip. Systems approach: New tool - light finishing and then roughing and then chamfering. Maximizes use of tool.

J. M. Hardy:

Data similar to those presented by Ford but divided by 4 (Ford/Deere x 4). Cut material weight for tools by 25% and still maintain cutting edges. Much of tool simply is platform for edges. Relationship between surface roughness and wear is not known. Cannot accurately predict tool life. Wear depends on machine tool rigidity - stiffer machine = longer life.

Manufacturing research - minimized cost is purpose. In foreign countries much more is done. More manufacturing research should be funded by Federal government. Incentives - relates to Justice Department. Information exchange needs to be made freer. Need Congressional or OST arm to foster research for needs other than NSF needs. Need education in accounting!

Is there a shopping list for needed research? Need applied research foundation - ARF. CIRP lists.

J. E. Mayer, Jr.:

Very little of the total tool material is worn off from each metalcutting tool during use. This is the case for both carbide and high-speed steel (HSS) tools. The worn carbide tools are generally not reground, but are sold as carbide scrap. The HSS tools are typically reground, and this reconditioning removes a significant portion of the total tool material over the life of the tool. The remaining HSS tool is sold as tool steel scrap. The replacement costs for metalcutting tools include the initial purchase cost, the tool changing cost and the regrinding cost for those tools which are resharpened.

More specifically, it is estimated that about 7 million pounds of carbide tools and about 41 million pounds of HSS tools are used in the U. S. A. per year. Only about 0.3% of each carbide tool is worn away, the remaining tool material is recycled into rock bits and tire studs, but not into metalcutting tools again. About 1/3 of each HSS tool is ground away during the resharpening process for this type of tooling, the remaining tool material is recycled but not into metalcutting tools. It was also estimated that the total cost of tool purchase, tool changing, and tool regrinding in the U. S. A. is about \$2.8 billion per year including labor costs, but not including overhead costs and lost production costs.

It was felt that optimum wear control procedures regarding application of best tool materials and designs are followed to the extent that resources permit, particularly in mass production industries. Tool life could possibly be improved by broader application of improved tool materials.

Since the greatest material consumption is with HSS tools, as a result of regrinding of these tools, it appears that new development should be directed toward improved materials for HSS tool applications. However, because of strategic material reasons, alternates for use of tungsten carbide are required, one possibility is titanium carbide.

No attempt was made at establishing whether the amounts of materials used in the metalcutting tooling sector are large in comparison to the total usage of these materials in the U. S. A.

2. Afternoon Session

Whole technology of cutting tools is based on tungsten. But we import 25% of W today and estimates indicate that this will increase to 80%. So should we develop technology with Ti or other indigenous materials? Also, average age of toolmakers in U. S. is 59. We need to train men!

GM developing own machine tools since industry has neither resources or inclination to do it. Aggregate of 1,270 machine tool builder's would not put them in Fortune "500" so GM will give results to country.

Profit-effective planning vs. cost-effective planning should be used to provide an incentive to make whole dollar package less expensive for Federal procurement.

Northrup report (Bob Pugh) - Manuf. Res. & Tech.

Surface integrity could improve if we had better cutting tools. It also might improve product durability.

Tooling approach has cut price of cutting edge so that per cutting edge, price is same in 1976 as it was in 1966 in constant dollars. Approximately \$70.

Material cost is 30 - 50% of retail price; processing is 50%. Cost is $\$400 \times 10^9$ for cutting of metal to provide finished goods. Cost in chipping tools is approximately $\$70 \times 10^9$.

Metal cutting machine tools = 2.7×10^6 in U.S.

Metal forming machine tools = $0.85 \times 10^6 + 0.1 \times 10^6$ in training situations (schools).

Machine tools - 174,000 in Government storage.

NC = 30,000 today = 1% of market but 25% of dollar volume.

The metric system could slow growth of CAM or numerical control.

Deere replaces machine tools because they are obsolete with respect to tooling or part processed. Very, very rarely does a machine wear out. The machine tool is durable enough now! Warner & Swasey does serious research - they disagree on wear of machine tools. They say wear occurs more rapidly. It bears investigation.

What are alternatives to using 20,000 tons of HSS as tools? None available at this time. If supply fails, then productivity drops drastically. There is need for research on reuse of HSS as tools; need more efficient use of tools. Largest seller is TPG carbide positive rake with 3 edges and is material inefficient.

Pay more for this edge than for 8 edges in SNU insert. Saves no more labor with TPG. Productivity decreases in terms of labor. But some machines (very few!) have no capability to use the SNU. Precision insert is not useful. Must take test cut first. Carbide inventories not carefully kept!

Replacement of cutting fluids - going to closed loop systems. With proper fluid maintenance, may need to change fluids perhaps once per year. Proper clean machine tools and keep clean. Disposal cost is 1.15 times cost of fluid not counting lost time. Energy is 500 kw/hrs per shift for pumping oil around.

More tools are wrecked regrinding them and using them.

Grinding wheels are consumed at great rate - one company gets back a boxcar per week of worn wheels.

There were $\$1.57 \times 10^9$ metalcutting machine volume in 1974. Including metal forming machines, this dollar volume is $\$2.14 \times 10^9$.

Need data base in order to specify designs to maximize wear durability for machined parts.

Can fund research associateships - transfer academics to industry for fixed period to determine needs. Must be funded at full parity.

R&D funds as a direct subsidy for research in this area.

- (1) Identify the need
- (2) Establish priority

Signal monitoring from tool could be used.

Data gathering by companies - need incentives to contribute to technology transfer.

B. TECHNICAL PAPERS PRESENTED AT SEMINAR #4

1. "Conservation of Strategic Imported Materials" by R. F. Bunshah

The U.S. Industry Outlook published by the U.S. Department of Commerce lists the following as the cost and weight of cutting tools used in the United States in 1974.

	<u>Cost (\$ Million)</u>	<u>Weight (Million lbs.)</u>
Carbide Tools	435	6.9
High Speed Steel Tools	470	40.8

The carbide tools are not resharpened after use but discarded as scrap and recycled for use in non-critical applications such as tire studs. The high speed steel tools are resharpened and about 1/3 of the tool weight, i.e., 13 million pounds is irretrievably lost in grinding. The worn tools are sold as scrap for recycling to medium alloy steels but are not recycled to high speed tool steels. It is estimated that about 10% of the 40 million pounds is thus recycled. Thus, it is apparent that both carbide tools and high speed steel tools must be made from virgin materials many of which are strategic materials and imported into the United States. The Table below estimates the quantity of alloying elements W, Cr, Co, V, which go into the manufacture of these tools. For the purposes of these calculations it is assumed that all carbide tools have a composition WC-10Co, all high speed steel tools have a composition of Fe-18W-4Cr-1V. The latter allows us to err on the conservative side since many high speed steels contain much less W and substitute Mo for tungsten.

	<u>Total Weight</u>	<u>W</u>	<u>Weight of Cr</u>	<u>V</u>	<u>Co</u>
(all quantities in millions of pounds per year) 1974 basis					
Carbide tools	6.9	6.2			0.7
High Speed Steel Tools	40.8	<u>7.3</u>	<u>1.63</u>	<u>0.4</u>	—
Total		13.5	1.63	0.4	0.7

The above represents a very large amount of strategic material imported into the United States. If by coating these tools with TiC and similar coatings (Ti is in plentiful supply in the USA), one can improve the tool life by 200 to 500% as has been demonstrated, a very substantial savings in tool cost and in the amount of strategic materials that we imported could be realized. An amount one-third or one-half of the above would not be unreasonable.

2. "The Problem of Wear in Metal-Cutting" by R. F. Bunshah

The cost of metal removal (labor and associated expenses) is about 75 billion dollars annually in the United States. The cost of cutting tools annually is 100 million dollars which is equally split between high speed steel and cemented carbide tools. Both types of tool materials are necessary. Carbide tools have a higher productivity rate than high speed steel tools, i.e., greater machining speeds, longer tool life, etc. Tools of simple shapes, e.g., tool bits, simple drills, etc. can be readily fabricated from cemented carbide starting stock. However, for complex tools, end mills, reamers, fabrication from carbide becomes extremely expensive since carbide stock has to be machined with diamond tooling. Moreover, carbide tools are very susceptible to fracture since the basic carbide material is brittle as compared to high speed steel. Hence, many complex tools are made from high speed steel. For example, a complex drill can cost \$500 when fabricated from carbides stock and \$50 when fabricated from high speed steel. The slightest mishandling of such a drill when made from carbide will cause it to fail completely by brittle fracture of the tip whereas the corresponding high speed steel drill is much more forgiving. Hence, the economic trade-off would probably favor the high speed steel drill in spite of the slower rates of machining.

The problem of wear control in metallurgy reduces to maximizing the TOOL LIFE and MACHINING RATES. One obvious answer has been the development of better or longer lasting tool materials. The evolution of tool materials, tool steels, high speed tool steels, cemented carbide tools, ceramic tools, diamond tools over the last 30 years attests to this. Since diamond tools are very expensive, a considerable effort has been put into coating the inexpensive tool steel and cemented carbide tools to improve tool life. About 1968 or 1969, chemical vapor deposition (CVD) techniques were applied commercially to coat cemented carbide tools resulting in an improvement in tool life by a factor of 3 to 10. CVD techniques cannot be used to coat high speed steel tools since the deposition temperature is too high ($\sim 1100^{\circ}\text{C}$) and would result in tempering and softening of the tool. Within the last year, physical vapor deposition (PVD)

techniques have been used to coat both high speed steel and carbide tools producing similar improvements in tool life by factors of 3 to 10. With the versatility of PVD techniques in their ability to deposit various types of complex materials easily, one can hope to vary the properties of the coating to tailor it to specific applications and to produce even greater improvements in tool life. Therefore, the stage is set for a two-pronged approach to improving cutting tools:

- Transfer existing PVD coatings from the laboratory to pilot production and production coatings for high speed steel and carbide tools.
- Develop new coatings tailored to specific cutting applications. For example, what is the toughness of a coating and how does it perform for continuous cutting vs. interrupted cutting!

One can modestly project that a 10% reduction in machining costs and a 30% reduction in amount of tools used should be well within the near term technological developments. This translates to a savings of \$7.5 billion a year in machining costs and \$30 million in tool costs, which is not an insignificant fraction of the GNP. The costs of such a program would be about \$1-2 million over a 3 year period, which is an attractive return of investment. It is up to the Government-Industry partnership to bring this about.

3. "Wear Costs of Metalcutting Tools, Machine Tools, and Cutting Fluid" by John E. Mayer, Jr.

a. Metalcutting Tools

Very little of the total tool material is worn off from each metalcutting tool during use. This is the case for both carbide and high speed steel tools. The work carbide tools are generally not reground, but are sold as carbide scrap, presumably for reuse or reclaiming. The high speed steel tools are typically reground, and this reconditioning removes a significant portion of the total tool material over the life of the tool. The remaining tool is sold as tool steel scrap for recycling.

1. Replacement costs

The replacement costs for metalcutting tools include the initial purchase cost, the tool changing cost, and the regrinding cost for those tools which are resharpened. All values given in the following are estimates. A U.S. automobile industry estimate might be made by multiplying the Ford values by a factor of about three.

2. Initial purchase cost and material and tool wear

• Carbide Tools. The estimated of units/year, pounds/year, and amount of wear are based on an assumption of 1/2 inch square x 3/16 inch tool insert with 0.035 inch flank wear as a typical tool. The purchased material total weight less the total weight of wear is the total weight of worn tools. Worn carbide tools are sold as carbide scrap.

3. Tool changing cost

Estimates are made for the tool change time for each tool material, total downtime for tool changing, and the labor cost for tool changing assuming a \$9.50 per hour labor rate. In order to obtain total cost for the tool changing, an appropriate overhead rate should be added to the labor rate (for 1974 an overhead factor of 2.27 utilized by National Bureau of Standards).

	<u>Tool Change Time for Each Tool, Min.</u>	<u>Total Downtime for Tool Changing, Million Hrs/Yr</u>	<u>Total Tool Change Labor Cost, Million Dollars/Yr</u>
<u>Carbide Tools:</u>			
Ford	1	1.87	17.7
U. S.	1	44.5	422.8
<u>HSS Tools:</u>			
Ford	4	8.67	82.4
U. S.	4	104.7	994.7

Loss of productivity due to tool change is estimated as 3 to 10%.

4. Regrinding cost

An estimate of the total regrinding cost was made assuming that the regrinding cost is 50% to 100% of the original purchase cost. Only HSS tools are considered to be reground. Tool regrinding costs based on total tool life may range from 100% to 300% for critical high speed steel tools.

Total Regrinding Cost, Million Dollars/Yr

HSS Tools:

Ford	20 - 40
U. S.	235 - 470

At Ford, purchase cost and regrinding of tools without including overhead or loss of production was \$2,000,000.

- Optimum wear control procedures regarding application of best tool materials and designs are followed to the extent that resources permit. Newest improved tool materials, e.g., ceramics, ceramic coated, TiC coated, sintered TiC, powder metal HSS, are being evaluated and applied as time permits. In order to be put into production use, however, tools must be cost effective.
- When optimum procedures (best available technological procedures) are not in effect, it most likely would be due to:
 - (1) Lack of knowledge but also lack of "know-how" on the appropriate application areas for new tool materials. Effect of wear --
 - specification for designers to obtain desired functional characteristics.
 - manufacturing practices to produce desired functional integrity.
 - (2) Lack of sufficient effort to permit extensive evaluation of newer cutting tool materials.
 - Need to develop methodology for cutting tool wear evaluation.
 - Continuing effort should be promoted for existing cutting materials.

- Tool life could possibly be increased by broader application of improved tool materials, including coated tools, wear resistance solid film lubricants, powder metals, etc. It is difficult to estimate what the improvement would be in cost and material. There would have to be a net decrease in cost in order to be put on the job. This broader application would require increased effort, which, of course, would require additional funding.

The greatest material consumption is with HSS tools, as a result of regrinding of these tools. Therefore, it appears that new developments should be directed toward improved materials for HSS tool applications. Because of strategic reasons, alternates for use of tungsten carbide are required.

- A form of life-cycle costing can be applied to cutting tools. This method computes the cost per piece machined by summing up the labor and overhead cost for the machining time, nonmachining time, and tool changing time during the machine cycle plus the total cost. In this manner tool cost can be balanced against labor and overhead cost. This method is not extensively being used in industry, but is gaining ground.

In addition to life-cycle costing, strategic importance of cutting tools such as tungsten carbide must be evaluated and alternatives developed. The total life cycle approach including work materials, energy, as well as costs mentioned above should be considered.

- Programs for reduction of tool costs are believed to be established, in general, in mass production plants, although not widespread industrywide.
- Improved tool wear resistance technology is implemented through laboratory and shop tests. Mass production industries do a fairly reasonable job of attempting application on newer tool materials. In general, tool wear technology is not implemented in industry.

b. Machining Tools

1. Replacement

- Material and Economic costs of machining tools. Machine tools are not removed/replaced because they have worn out. Change due to:

- Loss of operational capability (speed, horsepower, accuracy, rate of metal removal).
- New operation (new technology)

2. Scheduled maintenance

Scheduled at nonproductive time.

3. Unscheduled maintenance

Generally due to failure of cutting edge. Reason may be due to the following:

- Poor cutting edge
- Work material
- Lack of cutting fluid
- Failure of hydraulic and moving part of machine tool either due to overload or cutting fluid penetration.

c. Cutting Fluids

Replacement costs involve the following considerations:

- Cleaner machine tools
- Proper proportions
- Maintain concentration
- Water quality

It cost 115% of cutting fluid cost to dispose it. Energy cost in pumping the fluid is significant. Lack of knowledge in technology transfer in cutting fluids reflects on functional characteristics of parts produced.

C. PARTICIPANTS/INVITEES AT SEMINAR #4

<u>Name</u>	<u>Affiliation</u>
Vijay A. Tipnis - Chairman	Metcut Research Assoc. Inc., Cincinnati, OH
Maj-Britt K. Gabel	Naval Air Development Center, Warminster, PA
John E. Mayer, Jr.	Ford Motor Company, Dearborn, MI
Robert E. Matt	Aerojet-General Corp., Sacramento, CA
H. Yakowitz	OTA, Washington, D.C.
James Galimberti	Kennametal Inc., Latrobe, PA
J. H. Doyle	Amer. Oil & Supply Co., Newark, NJ
R. F. Bunshah	UCLA, Los Angeles, CA
Charles H. Kahng	Michigan Technological Univ., Houghton, MI
E. J. Weller	Master Chemical Corp., Perrysburg, OH
D. V. Minuti	Naval Air Development Center, Warminster, PA
B. F. von Turkovich	Univ. of Vermont, Burlington, VT
Anderson Ashburn	American Machinist, McGraw-Hill, NY, NY
J. M. Hardy	Deere & Co., Moline, IL

CHAPTER XI
SEMINAR #5: RAILROAD ROLLING STOCK

A. MINUTES

It was decided by the participants of seminar #5 that they would accept unanimously the report submitted by their Chairman*. Due to this decision, no minutes were submitted for inclusion in the workshop proceedings.

B. TECHNICAL PAPERS PRESENTED AT SEMINAR #5

1. "Diesel Electric Locomotives" by S. R. Callaway

a. Introduction.

These remarks reflect my company's experience as a manufacturer of diesel electric locomotives. We do not presume to speak as representatives of the U. S. railroads, but we believe our long association with them as suppliers of motive power gives us an insight into and an appreciation of their problems, especially as they may deal with the subject of this meeting.

I shall comment about wear in the limited sense — meaning the loss of material by attrition from either of two abutting surfaces which rub, pound or slide against each other — and in the broader sense — meaning the premature scrapping of a product for any reason before it has physically worn out.

We sell capital goods, not consumer items. Our customers are concerned with costs of acquisition, operation, maintenance and replacement as well as return on investment, and they have the accounting capability to evaluate them.

b. Product Life and Warranty.

Diesel electric locomotives have a very long useful economic life. Although a life of fifteen years has been claimed, the actual physical life is much longer.

As of January 1, 1974, about half of the 16,842 locomotives on 26 major U. S. Railroads (about 65% of U. S. total fleet) were more than 15 years old. The GP-7 general purpose road-switching locomotive introduced in 1949 is a very good example. A total of 2619 of these were built between 1949 and 1954. As of January 1, 1974, 2448, or 93.5% were still in service after more than twenty years!!

*The Chairman's Report for seminar #5 can be found in Chapter II, Section E.

A basic company policy is to maintain parts service for locomotives which we have built, hence units need not be retired for lack of parts availability. Except for units which may be damaged beyond repair in a wreck, locomotive life is more likely to be set by economic obsolescence than by physical wearing out of components. It is advantageous for the owner to replace an obsolete unit when he can buy a newer locomotive which does more work at less cost and gives a much greater return on investment.

The manufacturer's warranty is consistent with this long life. Originally for one year or 100,000 miles (whichever came first) this was increased to two years or 250,000 miles a number of years ago. In mainline service, locomotives typically accumulate mileage at a rate of 150,000 to 200,000 miles per year, with some newer units in high speed freight service approaching 250,000 miles annually. These figures project to a minimum of 3 million and a maximum of 5 million miles over a twenty year period.

c. Unit Exchange, Remanufacture and Upgrading.

Maintenance cost and locomotive out-of-service time for major component repair and replacement has been minimized by unit exchange. This is a concept whereby the manufacturer maintains a pool of such major components as engines, generators and traction motors which have been manufactured and upgraded to meet production standards.

A customer who requires a traction motor replacement can order it for immediate shipment from the pool and return his old motor for repairs. He will be charged commensurate with the cost of repair and upgrading his old motor to rebuild pool standards. Work is also done on a "repair and return" basis for customers who want their own components back, but they lose the advantage of immediate replacement, since they must wait for repairs to be completed before the component is returned.

When a locomotive becomes economically obsolete as an operating unit, it still contains many components which have economic utility. Re-manufacturing takes advantage of this residual value by bringing them up to current standards so that they may be used in modern motive power with current warranty obligations in the locomotive replacement program.

Specific examples where this can be done include truck frames, bolsters, traction motors, generators, crankshafts, camshafts, turbochargers and roots blowers, to name just a few.

d. Design Philosophy.

The application of new technology appeals to all engineers, and we are no different from others in that respect. We want to apply new technology to our products, and we continuously evaluate technical developments with that thought in mind.

We have imposed upon ourselves a very important constraint, however, which is that the economic return and technical benefits derived from any change must justify its cost over the life of the locomotive. This makes our engineering challenge more difficult.

This rationale may not be recognized or even understood by those unfamiliar with our product line and the railroad industry. It may not be intuitively obvious that we should not start fresh (with a clean sheet of paper) and abandon all previous designs when we set about to design a new component or end product.

For example, locomotives typically are not used as single units but are operated in multiple with others. Any locomotive we build must be capable of multiple unit operation with all previous models, both our own and those built by competitors. This then brings us to consideration of some other constraints which guide and dictate design of our products.

e. Component Interchangeability.

Even as we improve product performance through the design of individual components, we require that, to the maximum extent possible, these newer designs shall be compatible with earlier models and be capable of retrofitting into them. Two examples will serve to illustrate this point.

What we call a power assembly in the engine consists of a cylinder head, cylinder liner, piston, and connecting rod. Continuous refinements are being and have been made in each of these components to upgrade reliability and performance and yet the external dimensions of the assembly have not been altered and hence it is possible to install today's power assembly into any earlier engine or equal displacement. Thus, the product is not only maintained to its original design standards, but in many cases is upgraded to more current standards and performance.

Another example is the traction motor used to drive the locomotive. External physical dimensions of the traction motor have not been changed, yet the traction capability and power output of this motor have been more than doubled and the reliability has also increased correspondingly.

These gains in performance and durability have reflected application of both new materials and design technology. Performance of our present motor at these maximum ratings is achieved with a failure rate of approximately 1.5% in the warranty period. A recent study on a major railroad indicated that 80% of the original equipment motors are expected to run 1 million miles.

A consequence of maintaining maximum component interchangeability is that the design process becomes evolutionary. The designer's challenge is to realize the benefits of improved performance or function in a component or assembly without making modifications which render it non-interchangeable with parts of similar function already in service unless the advantage gained

can clearly justify doing so. This seems to be a challenge often overlooked by people new to the railroad industry.

f. Product Reliability.

An obvious way to minimize material consumption and replacement cost is to extend product life by improving reliability. Such a program requires that one must first know what the life and/or replacement statistics are for individual components and major sub-assemblies.

Because locomotives are delivered directly to the railroads from the manufacturing plant and our service personnel are in close contact with the railroads, we have always had good feedback on product performance and field problems.

For a number of years, we have quantitatively analyzed this information using Weibull statistical techniques. From a known population of a specific component in service and the field reports on replacements with respect to time, the Weibull analysis allows us to predict the total percentage of failures (or survivors) at a future time.

The design group responsible for a particular set of components establishes reliability goals for them and utilizes the Weibull analysis to monitor progress in meeting the established standards. Because reliable information on component performance can be expected throughout the warranty period, the Weibull analysis allows a projection to be made for greater time periods.

Another important part of the product reliability program is the definition of performance standards for many purchased components which spell out the performance capability and durability expected of these components under specified test conditions. Newly designed components or those from new sources of supply are tested prior to their release for quantity production to be sure that they meet performance and reliability standards necessary to satisfy end product requirements.

g. Reducing Wear Cost.

By the very nature of their service environment and function, some components will be more subject to wear than others. Both materials technology and design can be utilized to minimize replacement costs for high wear items. These are several well-recognized materials engineering approaches to wear reduction.

Harder and more abrasion resistant materials can be used. Durability of wearing surfaces can be increased by hard facing deposits, hard chromium or electroless nickel plating, and sometimes the application of dry film lubricants

or chemical conversion coatings which reduce friction are very effective. In some cases, the use of a softer material such as rubber or a polymer has been effective in reducing wear.

One design concept which greatly reduced wear and the consequent material replacement cost was the development of locomotive dynamic braking. This reduces the need for using air brakes on the train and results in major savings in brake shoe and wheel material, (Over 1500 pounds of brake shoes per round trip of Santa Fe El Capitan - Chicago to Los Angeles.)

Another design approach to reducing wear costs recognizes that it may be more economical to provide for easy low cost replacement of a high wear item than to utilize a more wear resistant material which can cost more and present major problems in manufacture and application.

The use of replaceable wear plates in many areas on the truck represents a prime example of this philosophy. In the engine, the lower cylinder liner insert and cylinder head seat ring are similar examples of replaceable items used at high wear points to protect and extend the life of the power pack and the crankcase which are much more expensive components.

Because the selection of a material for a specific end use involves a number of criteria such as mechanical strength, processing capability and resistance to elevated temperature or corrosion, these factors cannot be ignored in selecting a material to minimize wear. Material practices used in manufacture of piston rings and crankshafts illustrate this point.

Compression piston rings used in our engine were originally alloyed gray cast iron with flake type graphite distribution. Grooves in the wearing face of these rings were filled with a proprietary magnetic iron oxide compound and the entire ring was heat treated to develop an iron oxide surface which has excellent antifriction and anti-wearing characteristics.

To increase mechanical strength of the ring, the base material was later changed to a malleable iron composition with the same surface treatment. With the advent of turbocharging on our engine, the base material for compression rings was changed to a spheroidal graphite (nodular) cast iron with greater fatigue resistance and the wear resistance on the sliding face was increased by adoption on a hard chromium plated layer.

Most recently, a heat treated stainless steel top ring has been used to increase wear resistance and related resistance to breakage, thereby extending the change-out period.

The crankshaft for our engine has always been made of a heat treated medium carbon alloy steel. The first step to increase wear resistance of the crankshaft was the adoption of induction hardening of main bearing and crankpin journal surfaces.

For many years, it was the practice when crankpins and mains were beyond acceptable limits to grind them undersize and use corresponding undersized bearings for mounting. Although this extended the life of the crankshaft, it was necessary to stock a supply of all different bearing sizes wherever crankshaft replacements were to be made and usually to mark each engine showing the size bearings which had been installed.

The use of undersize bearings was abandoned more than 15 years ago in favor of the practice of bringing all main bearing and crankpin journals back to standard size by hard chromium plating. The economic advantages of having to stock only one size of crankpin and main bearings are obvious.

The cost of salvaging a crankshaft by chromium plating depends upon the number of journals and thickness of chromium to be deposited. However, the saving realized by the customer in having a crankshaft chromium plated as compared to the purchase of a new crankshaft is substantial. For example, plating .010" chromium per side on the main bearings and crankpin journals of a 16 cylinder crankshaft costs less than 25% of the price of a new shaft.

Although we did modify our engine to increase cylinder displacement about ten years ago, we have maintained the same cylinder spacing and piston stroke which means that crankshaft interchangeability has been maintained throughout the history of our engine even through horsepower ratings have increased from 1350 in 1939 to 3000 tractive horsepower in today's 16 cylinder engine.

h. Maintenance Costs.

Reports filed by railroads with the United State Interstate Commerce Commission covering the cost of repair and fuel for all locomotives operated provide quantitative information on operating and maintenance cost.

The latest available data are for the year 1972 and indicate that repair costs of approximately \$665 million represented slightly less than 36¢ per thousand gross ton-miles of service.

Oliver Wendell Holmes wrote of the Deacon's Masterpiece - "The Wonderful One Horse Shay" in which each part was as strong as every other and all wore out simultaneously. This ideal is not attainable in the real world because parts do wear at different rates.

This is recognized in setting maintenance schedules so that the shortest life items are easily replaceable at time intervals coinciding with minor maintenance and the longer items can be replaced at the time of major overhaul.

The task of designers and engineers is to be sure that the useful life of each component will coincide with the appropriate maintenance schedule and it will not be necessary to take a unit out of service for unscheduled maintenance because of component wear or failure.

Filtration of air, fuel and lubricating oil extends the life of major engine components by removing particles which would otherwise accelerate wear rates. Replacement of filter elements at scheduled time intervals, or when lubricating oil analysis for example indicates the need to do so, is a relatively simple and low cost operation. When done in accordance with manufacturer's recommendations, it pays good dividends to the customer in protecting and extending the life of more expensive components.

1. Summary.

Each speaker at this seminar was asked to consider both design practices and maintenance practices in responding to the question of whether optimum wear control procedures are followed in his industry. An evaluation of what constitutes OPTIMUM wear control procedures implies there are standards to make such a judgement, and there might be as many opinions about that as there are people sitting in this room. Nevertheless, when consideration is given to all of the conflicting forces, both technical and economic involved in locomotive design and maintenance, we believe that EFFECTIVE wear control practices are followed.

I hope that the foregoing remarks have served to illustrate the way in which we as manufacturers approach the task of controlling and minimizing costs of wear in railroad motive power and have given you some quantitative or at least semi-quantitative measure of our success in meeting this objective.

2. "Material Conservation Potential in the Railroad Journal Roller Bearing" by Gerald J. Moyer

The modern compact high capacity roller bearing unit realizes, by its low weight design and maintainability, significant material savings compared to the heavy journal box types. The standard journal roller bearing, introduced in significant numbers in the 1960's and now totaling some one million car sets, has dramatically reduced "set-outs" in comparison to the solid journal bearing. Nevertheless, there is potential for additional materials savings through improvements in design of bearing related components, maintenance, remanufacturing, original manufacturing efficiency and most importantly, better adaptation to, and wear reduction in, rail and truck components.

While the failure rate of roller bearings is still quite low, there are indications that its full service life potential is not being realized. Component "wear-out"

in the sense of gradual metal loss is not a significant failure mode, yet the number of loose components and lubrication related "hot boxes" as well as the approximately 20% rate of replacement of nine year average age components when bearings are routinely reworked due to removal for other causes, is a concern to the industry. Plastic deformation in the form of raceway brinells as well as oversize rings resulting from repeated high loading is a major cause for component replacement.

The Industry is introducing a number of product and maintenance improvements. These include the so-called No Field Lube adaptation, fitted backing rings, tighter inner ring/journal fits and continually improved seal and lubricant technology. In addition, a beginning has been made in the practice of "true" remanufacturing or recycling by means of remachining, regrinding or partially reheat treating.

Bearing performance and life cycle costs ultimately depend on related system performance, wear out of rails, snubbers, adapters and the frequency of car derailments. Improvement in these areas will benefit the bearing through reduction of dynamic overloads as well as improved internal load distribution.

We should not overlook the potential material conservation through efficiency increases in original manufacturing. Machine stock reduction through better use of advanced metal forming and forging technology has a potential for reducing steel consumption by one third. A healthy economy and a stimulation of normal instincts are the only prerequisites.

3. "Abstract" of Discussion Presented by J. Kalousek

Macroscopic and microscopic observations of rail/wheel gauge and flange wear and rail corrugations are presented to illustrate that adhesive wear, plastic flow and surface fatigue are the most decisive factors in determining the life of rails in curves under especially heavy traffic densities and loads.

Cost effectiveness of present lubrication policy is then evaluated. It is also shown that a 20% reduction in wear could result in additional savings of .0016 dollars/car mile on wheel changes and 100 dollars/MGT mile on rail replacement for curves on lines with annual traffic densities of 40 MGT.

4. "Projections for Long-term Improvement of Combined Wear, Fracture and Weldability Factors for Rail Steels" by William S. Pellini

a. Background

The presentation is abstracted from two position papers -- recently prepared by the author, as the result of analyses of metallurgical/mechanical/weldability factors. The analyses were requested by the AAR (Dr. W. J. Harris Jr.) for purposes of information in scoping future research and test directions. At this time, the objective of the papers is to stimulate discussions and debate on the issues presented -- by a wide circle of interested parties. The position papers are summarized in sections b and c, as follows.

b. Case for Metallurgical Optimization of Rail Steels -- Projections Beyond Practical Limits Imposed by the Historical Eutectoid Steels.

In the context of this presentation, the term "present" implies retention of the historical features of eutectoid-level carbon contents--typically in the 0.60% to 0.80% range.

The addition of relatively small amounts of alloy elements, and the use of special heat treatments are of interest for purposes of present day improvements of eutectoid steels for rail use. However, the eutectoid level carbon content serves as a severely limiting factor on projected attainments of improved properties. In fact, the interest is in squeezing-out the last vestiges of improvements--beyond which there is no reasonable expectation for other significant advances, for fundamental reasons of the eutectoid-level carbon content.

This paper is addressed to the question of what lies beyond this point of essentially complete exploitation of eutectoid carbon steels. A completely new philosophy, for the optimization of rail steels, must be evolved as the next sequential step. The new philosophy does not involve invention of new basic metallurgical principles. It may be evolved simply by a systems analyses of all primary requirements including --

- wear properties
- fracture resistance
- weldability
- life-cycle costs, and
- economic factors

The primary aspects of the metallurgical information, including fracture properties to be expected and weldability factors, are fully available in the context of present knowledge. All other aspects are a matter of usual methods of analyses of trade-offs for purposes of optimization of all factors of interest, ie, systems analysis.

It is not implied that a new rail for the future can be fully decided directly by the analyses. It is emphasized that the analyses can be made reasonably directly, for purposes of limiting the number of primary options. Experimental work will be required to examine the most reasonable set of options. Engineering decision can then be made for test and field evaluation of most promising selected compositions and heat treatments.

The historical origins of the most widely used rail steels in the USA, may be traced to the 1880-1890 period. Steels were a recent invention at this time and consisted strictly of various combinations of C and Mn. The effects of other alloy elements were not known.

It was logical at this time, to use a eutectoid steel composition -- centering on 0.60 to 0.80% C and 0.70 to 1.0% Mn. Higher carbon contents introduced hyper-eutectoid (massive) carbide microstructures that resulted in excessive brittleness -- as evidenced by tensile tests. The tensile test was first used during this period. In brief, the steels could be cited as being *tensile-test developed*.

The advantage of these early-type steels is that relatively high strength (hardness) could be obtained by simple heat treatment. This involved air cooling from rolling temperatures. Later, reheating to approximately 1600°F and air cooling (normalizing) was used also -- as well as slow cooling in the critical range for avoiding hydrogen flaking. These refinements retained the inherent simplicity of heat treatment -- typical of pearlitic steels.

The inherent disadvantage of the eutectoid -- pearlitic steels, is that of brittleness in the presence of notches or cracks. To the present day, all that can be done is to adjust the degree of brittleness -- the steels cannot be made fracture insensitive, for fundamental reasons.

The development of alloy steels, during the period of 1900 to 1930, was influenced by the use of early types of notch tests. For example, the Charpy V and Keyhole tests, developed in 1905. It was found that the carbon level must be limited to the range of 0.30 to 0.50%, in order to avoid excessive notch sensitivity at high and intermediate strength levels. The present "forging grades" of alloy steels were evolved during this period and were first used for armor plate, projectiles, bolting and machinery components.

Interest in welding, during the 1940 to 1960 period, resulted in new families of alloy steels -- with carbon contents limited to the 0.10 to 0.25% range -- for intermediate and high strength levels. The reason was the high hardness and consequent brittleness developed by hardenable alloy steels in the weld and heat-affected-zone, as welded.

These historical aspects of optimization for alloy steels -- involving successive decreases of carbon content -- should be considered in projecting for future optimization of rail steels.

If high hardness, combined with good fracture resistance and reliable as-welded joints are desired, it is essential to:

- (1) Limit carbon content to 0.30 to 0.40%
- (2) Add sufficient alloys to provide for lower bainite or martensite transformations -- without other split transformations (mixed structures) of high temperature type (pearlite and upper bainites).

These requirements represent a point of major departure, from the present trends in developing improved rail steels. These trends are based on adding small amounts of alloy elements and retaining the very high, eutectoid-carbon contents. These trends do not fully utilize the described metallurgical experience and logic -- because they can only lead to:

- (1) Continuing the use of a relatively brittle product
- (2) Introducing split transformations, that enhance brittleness with increase in strength level (hardness)
- (3) Preclude welding, except by the use of complicated preheat-postheat procedures

These trends can be described, as obtaining higher hardness for purposes of enhancing wear properties, at the expense of all other factors of equivalent importance. The other factors are enhanced brittleness and very poor weldability.

The only escape route, from these undesirable trade-offs in the interest of wear properties, is to fully use present knowledge on the transformational characteristics of alloy steels -- as related to heat treated and as-welded microstructures.

This knowledge directs the optimization procedure to the use of intermediate amounts of alloy elements; intermediate carbon contents; and heat treatment by quenching and tempering.

This logical route can provide rails of:

- The desired high levels of hardness for purposes of wear resistance.

- High fracture toughness that would eliminate sensitivity to cracks, and positively preclude fractures in service.
- Good weldability of low cost features and assured service reliability of the welded joint.

The importance of proper quenching and tempering is paramount. There is obvious need for new facilities for on-line heat treatment by Q & T. Batch type operations must be avoided for reasons of economy in manufacturing. Such facilities were deemed essential for producing standard grade Q & T steel plates and shapes -- intended for welded fabrication. It was the factor that made these steels economical and competitive with C-Mn steels on a strength to weight basis. The facilities investment is essential for purposes of projecting long term, high tonnage use of the future, optimized rails.

c. Fundamental Considerations That Apply to the Plastic Flow Systems Involved in the Wear of Wheel-Rail Interfaces.

Any connection between plastic flow theory and mechanisms of wear involving metal loss by crack formation, delamination, flaking, shelling, etc. -- must consider effects of intensity localized shearing displacements. In turn, connection to microstructural factors must be based on the same specific conditions of mechanical states for metal separation.

The existing literature on basic mechanisms of wear does not provide analyses that are reasonably related to the case of intensely localized shearing displacements of plastic flow, that evolves on the low-rail head -- particularly on the field side of curves. This does not say that various aspects of theories do not apply in part or a starting point. It does say that specialized extensions of the theories are required.

It is essential that a reasonable and realistic system of wear mechanism models be developed for conditions of variable constraint to plastic flow. The constraint variable is of geometric origin -- thus, the models must be referenced to geometric constraint parameters.

In order to design realistic wear tests, it is essential to reference the applicable (specific) model that is of engineering significance. This is the aspect that must be reproduced in a model (laboratory scale) test. Obviously, it is essential to analyze service conditions in terms of the mechanical constraint model that applies.

It is fundamental that the resistance to plastic flow is closely related to the system of mechanical constraint that in fact acts as a "resistance" factor. In other words, the plastic flow curve is not an intrinsic property of a steel of specified hardness. Constraint to plastic flow may be high or low depending on the mechanical system, as related to the geometry of free surfaces.

The development of cracks or delaminations is a highly localized event. Separations that start and enlarge in regions of intensely localized shearing displacements (bands) reflect conditions that are not typical of the bulk material. Local stresses and local strains are sensed by the metal grains undergoing separation. It is essential to focus attention to these stress/strain critical regions.

These considerations lead to a novel mechanism of wear (for the cited case) that involves highly localized, intensely active bands of plastic deformation. The effects of changes in bulk properties, such as hardness, are modified considerably -- to the degree that constraint acts to minimize or accentuate localized plastic flow. Fundamentally new forms of analyses are required for the problem of specialized wear conditions.

It is important to note that an increase in the hardness (tensile strength or compressive strength by usual references) of the surface results in different stress-strain relationships, for regions of low as compared to high geometric constraint. In brief, increase in the microstructural hardness of a rail results in either small or large effects on rail-head plastic flow, depending on the plastic constraint factor that applies to center or edge of the rail head.

Most importantly, plastic flow resistance is not intrinsic to a state of hardness. Discussions of hardness effects that do not include geometric constraint factors are grossly inadequate for purposes of defining wear mechanism or for relating to wear rates.

This model of "first principles" must now be modified by added considerations of -

- non uniform metal flow involving intense shearing displacements.
- hardness gradient effects.

A sharp interface between intensely deformed and undisturbed metal, is predictable from the shearing deformation (Ray) model. The only modification of the model (as discussed) is the addition of intense directional effects from an extrusion-like metal forming operation--consequent to indentation plus the contributing effects of a free surface of low constraint. For these conditions, the ray becomes close to planar-sheet dimensions, as observed.

An explanation is now provided for the development of a crack. The planar-sheet flow cuts-off sharply at a point that shearing stress fall below yield levels. The transition is sharp because sheet-dimension lamellar flow is involved. Rupture of the grain structure is to be expected at this critical interface, between intense shearing and no shearing.

The crack may be expected to progress by a fatigue-like mechanism. However, the crack progression does not appear to be by a crack-opening mode (fracture mechanics K_I) but by a type III (shearing mode). Thus, we simply replace K_I with K_{III} and retain the fatigue nomenclature-but with a different physical meaning.

There is considerable contention as to the merits of particular theories for specific cases. The scientific literature abounds with discussion of different theories for different situations.

Recently there has been emphasis on theories that include metallurgical/microstructural effects. Not surprisingly, the authors of noncontinuum theories direct their attention to wear processes that involve crack formation or delamination. An example, is provided by the work of N. P. Suh (MIT) on the delamination theory of wear. His experiments involve low speed sliding wear. The wear tracks are related to sites of sub-surface deformation, nucleation of voids and cracks, crack propagation, formation of thin wear sheets, etc.

Since the metal separation mechanism dominates for this type of wear (as enforced by experimental conditions) the connection to metallurgical structure is guaranteed.

The experiments in no way contradict the adhesion theory of Rabinowicz for conditions truly applicable for this theory. The adhesion theory predicts that when the ratio of surface energy to hardness is large, the coefficient of friction increases because the real area of contact at asperity points increases. This theory applies well when the wear particles are likely to be in the order of asperity contacts.

Conditions of wear that included generation of large wear particles - due to gross plastic flow and subsequent cracking - have led to theories involving fatigue as well as microstructural factors. Unfortunately, the fatigue theories are dominated by the existing literature on crack-opening-mode fatigue tests, as a basic reference point. This leads to visualizing crack opening stresses as a potent factor for fatigue crack extension.

All theories appear to have a proper fit to experimental facts, provided the mechanics of the plastic flow system are properly analyzed.

The analyses that are presented lead to predicting that a marriage of theories is required for any specific case of railroad-wear interest. In brief, no one theory fits all cases.

The model of intense shearing displacements (as planar sheets) is not new. It simply involves recognizing the nature of the micromechanical system that is acting to produce plastic flow-as an engineering responsibility in defining the effects of the railroad environment in question.

With this first step, we are then ready to look at wear theories that fit the circumstances. Usually, it will be necessary to extrapolate, modify or otherwise amend the theories-as required by the circumstances of macromechanical system.

Considerable basic information may be derived from the literature on metal forming as well as the literature on wear. In fact, the modifications of wear theory should be closely related to metal-flow theory for plastic forming.

5. "Ferrous Metal Wear and Resulting Maintenance on the Santa Fe Railway"
By Geoffrey E. Dahlman

The Santa Fe Railway consists of a 12,500 mile system of track which extends from Chicago to the Gulf of Mexico and to the Pacific Coast. The Railway has about 80,000 cars and 1700 locomotives. Most Railway activities involve movement of freight, much of it in interchange with other railroads. A limited amount of passenger service is operated by the Railway for Amtrak. Metal to metal wear is a major problem resulting in high maintenance on the Railway. Below six wear problems are discussed stating what the Santa Fe is doing about them.

a. Bolsters and Side Frames.

At our railroad shop in Topeka, Kansas we are reclaiming over 3000 bolsters and side frames annually due to wear in bolster gibs, friction shoe pockets, center plate rims, and side frame pedestals. The reclamation procedures are outlined in AAR Interchange Rules 47, 48, and 82. Welding materials used for build-up in worn areas are comparable in hardness (150-200 BHN) to the original bolster and side frame castings. Santa Fe is testing reclaimed bolsters and side frames with hardsurfacing materials applied. Also a couple of years ago we weld repaired two bolsters in the center strut area presently a prohibited repair per Rule 47. These two bolsters both passed fatigue tests at the AAR Tech. Center in Chicago. As a result we recommend revisions to Interchange Rules 47, 48, and 82 to allow more cost effective and extensive reclamation practices. These revisions would include specifying hardsurfacing materials for weld repairs and relaxation of the welding area limits. Approval for more extensive reclamation might be given on a limited basis depending on shop facilities.

b. Center Plates.

Mechanical personnel on the Santa Fe indicate body center plates are a major maintenance problem on freight cars. Premature failure is either the result of wear and/or fatigue cracking in the bowl-rim fillet. Our shop in Cleburne, Texas has an extensive center plate replacement program in progress. We are ordering flame hardened and manganese steel center plates for replacements.

Road testing results indicate a bowl bevel significantly reduces stresses in the bowl-rim fillet. We feel the present 3 degree bowl bevel specification should be revised to allow for a more generous bevel for we have not obtained the bevel on many center plates recently purchased.

c. Wheel Wear.

Santa Fe keeps extensive wheel application and removal records on our York Canyon Unit Coal Train. This unit train averages about 100,000 miles per year. Recent analysis indicates average mileage to scrap on a two wear class C wheel in this operation is 331,000 miles. Lowest mileage to scrap reported has been 108,000 and highest mileage 562,000. We have been puzzled in the past over the wide range of wheel mileage data on similar cars however the wide range is due to problems other than just wear which cause premature wheel removal, e.g. derailments, bearings, spalled tread. In 1973 a study on the Santa Fe was made investigating the causes of erratic wheel life. Braking operation was extensively studied, for at that time braking related defects were the largest single cause for wheel removals from the York Canyon Train. Three cars were selected for inspection at our San Bernadino Shops:

AT 74915-Account having good wheel mileage between changes

AT 74925-Account having 18 changes due to spalled tread

AT 74958-Account having 12 changes for thin flange

Individual brake pressures on the above cars were measured using special instrumented brake shoes (Golden Shoe). AT 74925 which had developed 18 pairs of spalled wheels was found to have considerably higher brake shoe pressures than the other two cars. Westinghouse Air Brake Company representative witnessed these tests but was only able to recommend a completely new foundation brake arrangement as a means of overcoming the problem. Wear is just one problem associated with wheel life.

d. Rail Wear.

In the past the Santa Fe used extensive amounts of Hi-Silicon rail in curves to reduce wear on the high rail and cold flow on the low rail. Recent work at the AAR and various field tests indicate heat treated high carbon rail is presently superior for curve applications. Supply of heat treated rail for the industry is marginal as evidenced by our attempts to purchase heat treated rail for over a year with no success. We will be receiving a shipment of USS Curvemaster rail in March and plan to run a field test of it versus the newly developed Chrome-Moly rail. Two curves will be used with half Chrome-Moly and half Curvemaster in each curve on the high rail only. Of course the rails will be transposed for low rail flow evaluation.

Currently we are inspecting every new "A" rail purchased with ultrasonics for seams and/or heavy segregation in the web. We began this program due to slowdowns in our automated welding lines when welding "A" rails, and the fact that 44% of our electric flash butt weld service failures in 1973-74 were

due to turned seams in "A" rails. "A" rails make up 20% of our rail purchases and of this 20% ultrasonic inspection results in a rejection rate of 20%. Therefore 4% of our rails we presently purchase are unsuitable for welding, and we consider defective.

e. Trailer Hitches on TOFC Cars.

Recent wear problems of hitches have developed primarily due to high speed truck hunting. Problem is being solved by heat treating present hitches (quench and temper) and use of constant contact resilient side bearings to reduce track hunting.

f. Piston Reclamation.

About one year ago the Santa Fe experienced a shortage of locomotive pistons. We had an excessive number of pistons failing prematurely due to scuffing in the piston skirt area. We experimentally reclaimed 20 pistons with aluminum bronze using thermal spraying techniques. Presently the pistons are under test in a locomotive with no reported problems.

6. "Wear of Rails" by D.H. Stone

To date the overwhelming majority of rail wear research has been strictly empirical. Specifically rails of different types have been placed in service, and the amount of metal lost in the rail head measured.

The Chessie System established the service test of heat-treated, alloy and standard rail on July 7, 1972 when the rails were installed in four curves on their No. 2 or east-bound main track west of Oakland, Maryland. A total of 80 rails consisting of 16 each of the five following types were used:

- (1) 140 RE Fully Heat-treated
- (2) 140 RE Head-Hardened
- (3) 140 RE Intermediate-Manganese
- (4) 140 RE Standard-Carbon Control-Cooled - A
- (5) 140 RE Standard-Carbon Control-Cooled - B

Four rails of each type were laid out for each of the four different curves, two on the high side and two on the low side of each curve. The rails were randomly welded

together in 10 rail strings by the electric flash-butt method. These continuously welded strings were then installed in the curves, one on the high side and one opposite on the low side of each of the four curves. The four test curves chosen for this test are of varying nominal curvature and superelevation as follows:

Curve No. 1, 5° - 50' (299.5 m radius) - 4 1/2 in. (114.3 mm) Superelevation

Curve No. 2, 8° - 28' (206.5 m radius) - 5 in. (127.0 mm) Superelevation

Curve No. 3, 4° - 00' (436.6 m radius) - 2 1/2 in. (63.0 mm) Superelevation

Curve No. 4, 8° - 08' (214.9 m radius) - 5 in. (127.0 mm) Superelevation

In general, low rail wear and metal flow and high rail curve wear has conformed to a pattern of more wear and flow in the standard and intermediate-manganese type rails and less wear and flow in the treated products such as head-hardened and fully heat-treated rails.

The amounts of wear recorded particularly in the high rails did not conform to a consistent pattern, but were erratic even with an averaging approach. Again, in general, the treated type rails did perform better than the others with the exception of the one standard type rail showing slightly less wear on the nominally eight and one-half degree curve than the head-hardened and the fully heat-treated rails, Figure XI-1.

The rather erratic wear pattern was evident also when comparison was made between the nominal degrees of curvature of the four test curves and the average wear of each of the five types of rail in test. The rather constant or slightly increasing average amount of wear calculated for the nominal four, six and eight degree curves in contrasted with the sharp increase for the nominal eight and one-half degree curve could have possibly been caused by or resulted from train speeds and the variations of curvature and superelevation as noted and recorded at the individual test rails in each of the curves.

This test is typical of many others which have been conducted in the past^{1,2} with only the amount of head removal reported in the form of profiles. Figure XI-2 shows an example of such data. While this data is useful as a relative comparison, it is rather

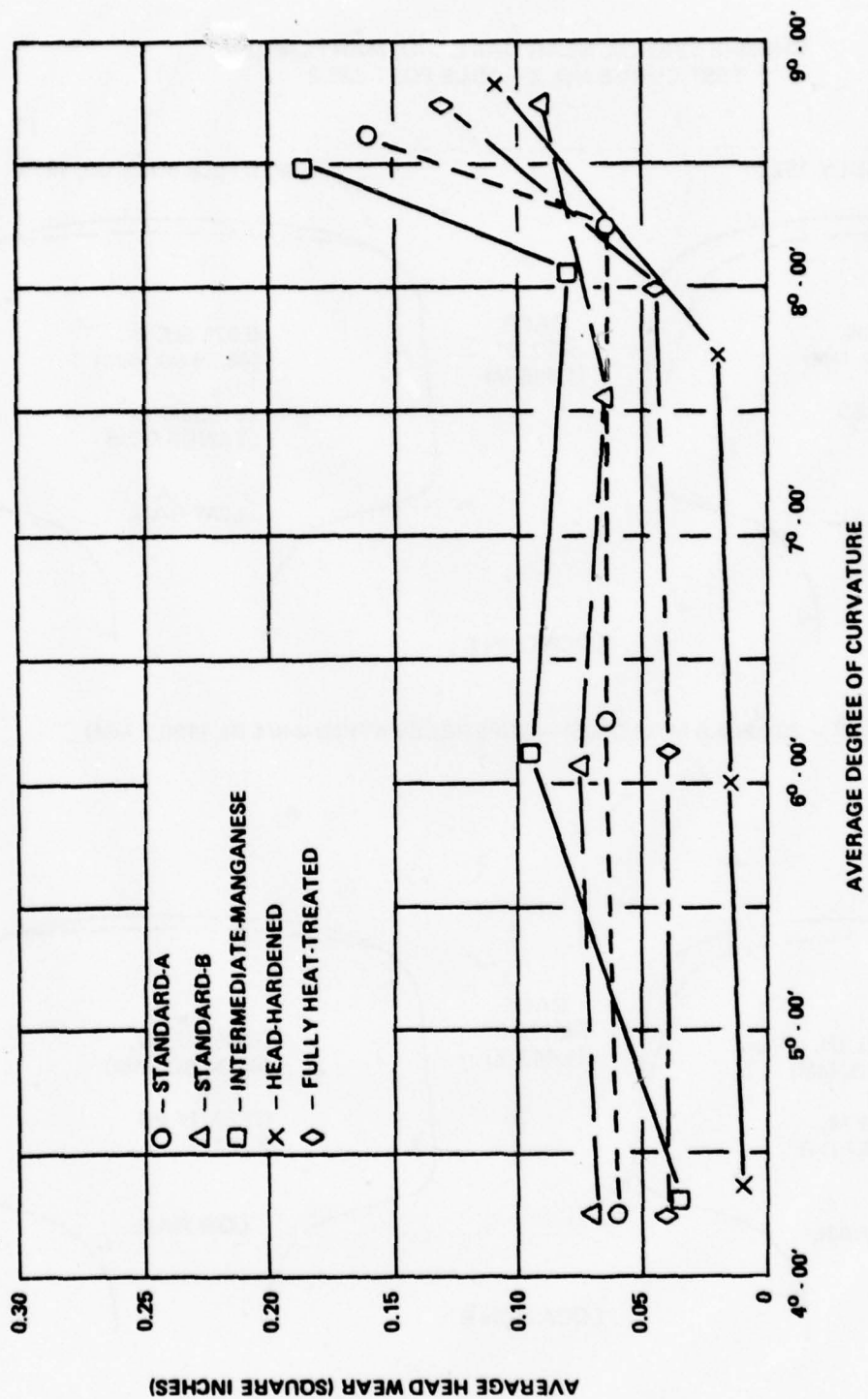
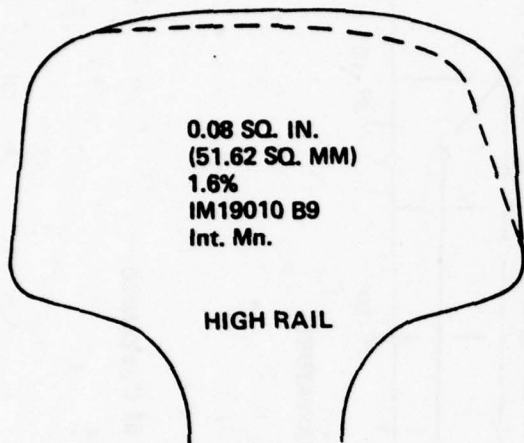


Figure XI-1. Average Degree of Curvature

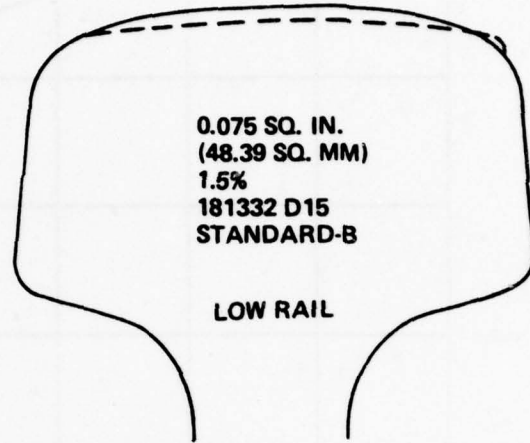
CHESSE SYSTEM, NEAR OAKLAND, MARYLAND
TEST CURVE NO. 2 - MILE POST 233.2

INSTALLED: JULY 1972

INSPECTED: JULY 30, 1974

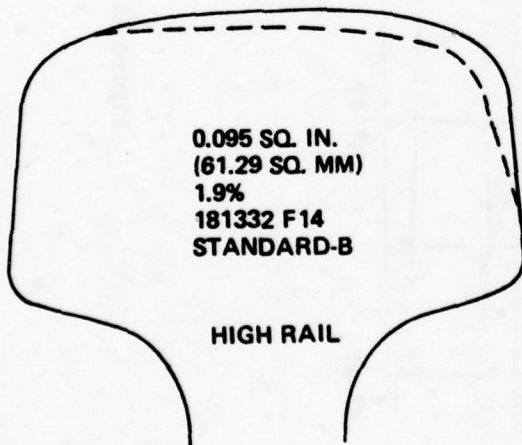


GAGE
56-7/8"
(1.445 M)

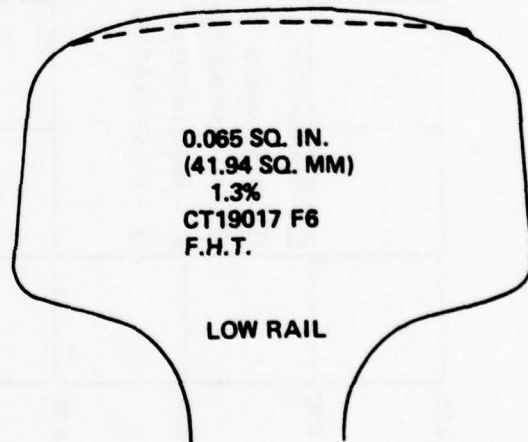


LOCATION 5

CURVATURE 8° - 30' (205.6 M RADIUS) - SUPERELEVATION 4-3/4 IN. (120.7 MM)



GAGE
56-13/16"
(1.443 M)



LOCATION 6

CURVATURE 8° - 45' (199.8 M RADIUS) - SUPERELEVATION 4-5/8 IN. (117.5 MM)

Figure XI-2. Chessie System, Near Oakland, Maryland Test Curve No. 2 -
Mile Post 233.2

unique to each individual test site. Further, without any knowledge of wear theory being used in the development of specific rail type, the wear is assessed when the rail development is completed and the rail in service. Because wear is the primary agent of rail removal, this is a cart before the horse situation which is certainly not an efficient use of research effort and expenditure.

Therefore, it seems wise that studies into the mechanisms of rail wear are overdue. Such studies would enable wear to be evaluated or approximated during development in its correct position as a primary concern.

a. References

1. K.W. Schoeneberg, "Summary of Heat-Treated and Alloy Rail Service Test Installations," AAR Report R-121, April 1973.
2. K.W. Schoeneberg, "Summary of Performance of Standard-Carbon and Various Wear Resistant Rails in Test Curves on the Chessie System," AAR Report R-171, April, 1975.
7. "Track Train Dynamics" by D.K. Sutliff

Phase II of Track Train Dynamics has as its major function the development of performance specifications for track structures, rolling stock and their components. Certainly one major element of judging the performance of track structures and vehicles is the degree to which dynamic performance capabilities as well as structural integrity is maintained. Both of these issues may be in many instances drastically affected by the degree to which the items are subject to wear during their service life.

The Track Train Dynamics project has recognized, therefore, that wear must play a significant part in establishing performance specifications. With charter of developing performance specifications for such a wide variety of items, it is obvious that our time and funds do not allow us to spend a great amount in the area of pure research as related to wear. We have, therefore, elected to select specific component areas which our experience, judgement, and intuition tells us are greatly affected by wear. Two such areas which were selected early on in the Phase II program for support by the FRA were those related to the wheel/rail wear situation and that relating to the

wear occurring between the car centerplate and truck centerbowl area. The basic physical phenomena leading to wear in these two component areas are thought to differ greatly. However, since these two research areas are of great practical interest to the industry, we have selected them as our initial topics for developing engineering solutions.

As mentioned earlier, the phenomena of wear can be manifested in several ways. In the case of the two research areas chosen for initial development by Track Train Dynamics, the wheel/rail wear area is perhaps best characterized as being a phenomena which causes rapid loss of material thereby ultimately leading to significant loss of structural integrity of both the components. The same can also be said to be true of the car centerplate-truck centerbowl areas.

On the other hand, when dealing with an area such as truck snubbing, wear can not only cause structural degradation but can change the dynamic characteristics of the truck suspension as well. Both this area and the area of rail and wheel wear will be discussed more thoroughly by TTD personnel today.

To date, the Track Train Dynamics Program, in dealing with wear, has elected to develop as rapidly as possible engineering solutions to the two above extremely important wear related problems. A further benefit however of the Track Train Dynamics Project comes from its position as a central location for coordinating various research activities relating to wear among other areas, as well as a repository for basic support information for other ongoing wear related research activities not within the scope of the Track Train Dynamics Project.

To this end, the Track Train Dynamics Project in conjunction with the Association of American Railroads stands ready to provide support to any railroad industry research activity dealing with wear to the extent that our time and funding allow. We feel it is exceptionally important that those conducting research in the area of wear for railroad related problems have a means of obtaining basic information as to the nature of the components, the physical phenomena, and the dynamic situations which lead to that wear. Only in this way can any research activity in the railroad industry lead to effective engineering solutions.

8. "Freight Car Couplers Wear Aspects" by Norman A. Morella

This report will cover freight car couplers, knuckles, yokes and draft gears. The present day replacement value of these components is estimated to be slightly over one billion dollars. In general, the life expectancy in terms of years of these components is quite long. Railroad reclaiming practices, of course, serve to extend the life.

The following lists the points of greatest wear on each component and also whether or not the wear point can be restored by welding or other approved method.

a. "E" Coupler (See Figure XI-3)

- (1) The rear of the keyslot (1) is subject to heavy wear and also upsetting of the metal at the corners. This area can be reclaimed by welding.
- (2) The butt area (2) is often peened and this, combined with a shortening of the coupler length, often requires a plate to be welded to the rear to restore the length. This area can also be built up with weld.
- (3) A hardened wear plate at point (3) is located at the point of greatest wear. This wear plate is replaceable. The freight car has a cooperating wear plate located on the carrier supporting the coupler. This plate is slightly softer than the coupler wear plate and is also replaceable. One question which should be addressed is the optimum hardness differences between the two wear plates for maximum wear life.
- (4) The knuckle wears principally on the pulling face point (4). The knuckle which functions as a "fuse" is supposed to fail at loads below those which would cause the coupler body or yoke to fail. As the knuckle wears, it loses strength and thus unnecessary train separations can occur. Wear at point (4) is not repairable.
- (5) There are several internal operating parts, point (5), which wear slowly and, in general, are not repairable by welding. The internal surfaces in the head of the coupler are not repairable.

b. Y-40 Type Yoke (See Figure XI-3)

- (1) The rubbing action of the draft gear and follower wear the yoke at point (1). The yoke rubbing against the yoke support plate wears the yoke at point (2). The weight of the draft gear tends to confine the wear to the lower yoke strap; however, it is railroad practice to turn the yoke upside down at least once to equalize the wear. Wear at points (1) and (2) is usually not repairable.
- (2) The crosskey wears the key slot at point (3). This wear is repairable.

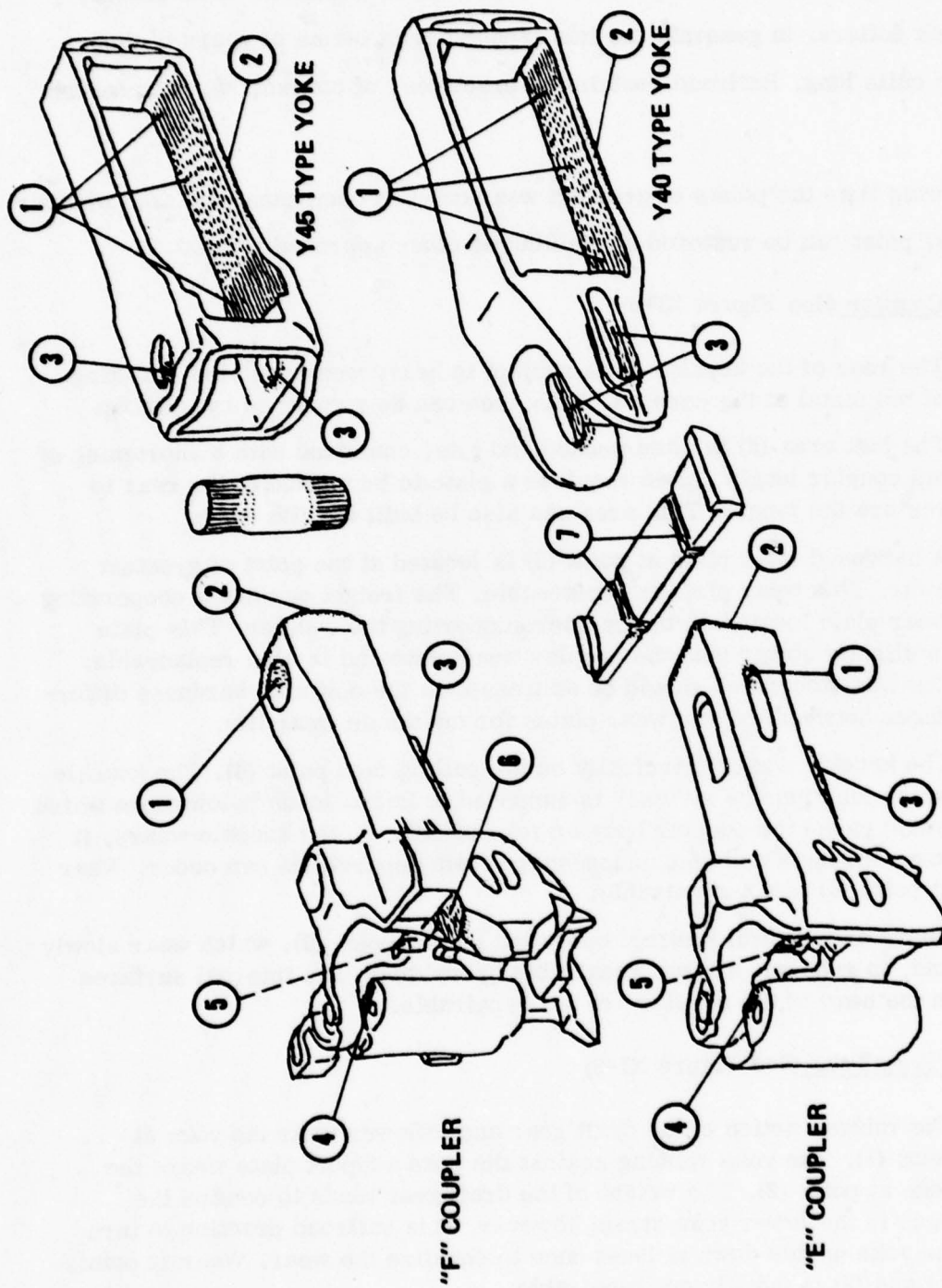


Figure XI-3. Y-40 Type Yoke

c. Crosskey

A combination of wear and metal upset contribute to making a key unrepairable. At times, reforging has been contemplated to reuse the key, but generally this has proven uneconomical.

d. "F" Type Coupler (See Figure XI-3)

- (1) The latest design of "F" coupler eliminates a pin bearing block at point (1) and increases the metal thickness. How this will affect the wear rate is unknown at this time. The earlier design had a bearing block which allowed the coupler to swivel about the pin. Studies by the Coupler Safety Project showed that the butt wear rate on TTX cars was on the order of .007 inches per 10,000 miles. This is the combined wear at (1) and (2).
- (2) With respect to points (3), (4) and (5), previous remarks for the "E" coupler apply.
- (3) Wear at the interlocking wings, point (6), is repairable.

e. Y-45 Type Yoke (See Figure XI-3)

- (1) The draft gear wears into the yoke at point (1) and the yoke support plate into the yoke at point (2). The yoke can be inverted to equalize the wear.
- (2) The wear caused by the pin occurs at the front of the hole, point (3). Welding is permitted to repair. Investigation is now under way as to whether the part could be bored and a bushing applied to make the part serviceable.

f. Pin

The pin is not repairable after it has become unserviceable.

g. Corrosion

Although these components are not painted or otherwise protected, corrosion is not a problem. Except for some passenger couplers, there are no machined surfaces.

h. Draft Gears

Draft gear wear generally takes place in the internal workings of the component and finally results in loss of ability to absorb energy. A majority of draft gears in service are the so-called friction draft gears which depend

on the friction between sliding steel components to absorb energy. Obviously, such a system is slated to wear, however, some estimates show that gears can last as long as 20 years in normal railroad service.

There are different draft gears which use an elastomeric rubber to absorb energy and these avoid the metal to metal wear associated with the friction gears. Rubber draft gears are used on locomotives almost exclusively and to a lesser extent on freight cars.

Repair of draft gears can be handled only in reclamation shops. According to AAR rules, gears removed which are more than 20 years old must be reclaimed. Reclaimed gears over 10 years old must be returned to reclamation shop for inspection.

i. Repair and Reclamation

Many railroads have set up reclamation shops to repair these components. The repair usually consists of replacing wear plates and building up section with weld. The reports of costs of reclamation have varied widely due to the various methods of costing at different railroads.

j. Life Cycle Costing

To our knowledge, no life cycle costing of the component is done by the railroad. However, from time to time, specifications and standard parts are upgraded by addition of wear plates, design changes or material changes to lengthen life. The increased costs of such changes are usually considered, but no rigorous cost/benefit study is made.

k. AAR Specifications

The "Field Manual of the A.A.R. Interchange Rules" governs the amount of wear that is allowed in components on cars moving through interchange points. Rules 16, 17, 18, 19, 20 and 21 cover couplers, yokes and draft gears. Any wear limits or gages are shown in these rules. Additionally, AAR Specification M-212 governs the reclamation of the aforementioned components.

9. "Implication for Materials Conservation"

a. Introduction

This report was prepared at the request of Professor E. Rabinowicz, Massachusetts Institute of Technology, in conjunction with the Office of Technology Assessment, the Workshop of Wear Reduction, and Seminar No. 5, Railroad Rolling Stock, to be held in Washington, D.C., February 23-25, 1976. This report will cover the broad industry aspects of wear technology

for the freight car truck, but is limited to American Steel Foundry's information on that subject.

The cost of maintenance to truck components is only 8% of the cost for freight car maintenance as we will discuss later in this report. This, however, does not define the total truck-related cost of maintenance. Maintenance of way and equipment, for instance, totaled over 5 billion dollars in 1974. It is unknown what portion of that figure is caused by adverse truck performance. The effect of truck performance can be hypothesized from force-frequency relationships, but this has not been a convincing argument for cost benefits of superior performance. Technology is available; there are trucks which perform with reduced punishment to the environment, but these have had limited application because of their higher initial cost. The absence of data relative to total maintenance costs attributable to the effects of the truck on track and car body structures, limits our ability to quantify the true cost of wear, and hence to justify this higher initial cost. There are industry projects attempting to do this. These are government-funded projects; namely, TTD (Track Train Dynamics) and TDOP (Truck Design Optimization Project).

This Workshop is concerned with material conservation as it relates to the design and material selection, and those aspects concerned with the prevention and maintenance for wear. ASF follows a multi-program approach for Railroad freight truck design each of which relate to materials selection and wear prevention:

- Optimize standardized Railroad freight truck components for extended life.
- Using the systems approach, design freight car trucks that provide improved performance. These can be non-standard components that will interface with standardized car bodies.
- Research is conducted in all aspects of materials selection and design at both a Metallurgical Research Lab and an Engineering Research Lab.

Our program for extending the life of our products includes formalized maintenance procedures and methods for rebuilding our trucks when necessary. We provide repair and maintenance manuals to the industry for our truck designs. Unfortunately, preventative, programmed maintenance, though likely the lowest in cost and in ultimate material use, is not yet widely practiced.

b. Wear and Maintenance Areas of the Freight Truck

The function of the freight car truck is to carry the car weight, to provide the interface between the rail and car body, and to provide the necessary suspension and damping characteristics for operation in the railroad environment. It also provides support for the braking system, and encompasses the wheel axle and bearing assembly, though these are not to be part of this report.

The subject truck parts include a bolster, side frames, brake beams, springs, and snubbing elements.

The areas of wear on a freight car truck are at those interface areas between:

Truck and Car Body

Bolster and Side Frames

Side Frames and Roller Bearing Adapters

Brake Beams and Truck

(1) Truck and car body interface.

- The truck bolster carries the car weight. Its center plate serves as the bearing surface and pivot, and must endure vertical, lateral and longitudinal forces from the various modes of activity from the dynamics of a car body.

Repairs to freight car truck equipment are made for several reasons, including damage from derailments, misuse, wear, etc. Repairs on the center plate of the bolster can be made without replacing the entire casting; either by welding, or the design of center plate can include a disposable wear liner. For those bolsters that do not have a wear liner, welding procedures for rebuilding the rim have been established. Rules and recommended practices for repairs in this area are available.

- Side bearings serve to support the car body laterally as required for non-level track, curves, etc.

Side bearings are a detachable part, and can be replaced when damaged or worn.

(2) Bolster and side frame interface.

- The interface between the truck bolster and side frames includes the built-in snubbing elements consisting of a coulomb friction device, its actuating springs, reaction surfaces, a friction/wear plate attached to the side frame, and a group of suspension springs. These items make up the suspension and control elements for dynamic performance of the truck.
- Other design features which wear and serve specific purposes include land areas on the truck bolster and side frames. These, in addition to anti-rotation stops, provide limits to longitudinal movement between the bolster and side frames. Gibs or lugs are also a design feature which provides limits to lateral motion between the bolster and side frame.

The suspension parts, including springs, friction wedge castings, and friction/wear plates, are replaceable items. The contact surfaces of the side frame and bolster castings, are repairable by weld procedures that have been established. This includes bolster pockets and gibs, side frame and bolster land surfaces.

(3) Side frame and roller bearing adapter interface.

The interface between the side frames and roller bearing adapters consist of an arrangement of lugs for maintaining wheel position relative to side frames. The pedestal roof serves to transmit the vertical load of the car to the wheels.

Pedestal repair procedures include the application of wear liners and rebuilding by weld methods.

(4) Brake beams and truck interface.

The interface between side frames and brake beams consist of a slide pocket on the side frame, and an extension on the brake beam. Necessary to the braking function are various pin connections such as dead lever lugs, and a pin connection of the brake beam.

The slide pockets are equipped new with a replaceable wear liner. Generally, brake beams are replaced because they have been damaged in accidents, and not because of wear.

c. Cost of Wear/Maintenance

The cost of repair materials is readily identifiable, and life cycle analysis can be applied; however, the published maintenance figures from existing data systems include repair materials for total maintenance for accidents, repairs and rebuilding programs, etc. To make a wear-related cost analysis more difficult, railroad operations and maintenance programs differ from company to company resulting in a variety of causes of maintenance and related effects. Also related and even more difficult to define because of the data system used, are the truck-related effects on wheels, track repair, car body maintenance, labor, cost of down time, etc. For example, wheel material is selected by some railroads to protect the track from wear, placing primary wear on wheels. Deferred maintenance on track has a compounding effect on wear and damage to the track, truck and car body.

We do develop life cycle figures for each wear area of a truck for specific operations, but as stated above, these differ considerably depending on the type of service. We believe the funded TDOP project is making an effort to and has progressed the furthest toward defining an over-all average cost analysis utilizing published and proprietary data. The effort may determine that a better data collection system is required before cost factors can be developed. We suggest that this project be invited to make a report to the Office of Technology Assessment.

We offer the following example of a life cycle cost of wear. Detailed inspections have been made on many freight cars to determine the life of the various areas of wear of a truck as described earlier. This example includes the cost of center plate repair, although we have inspected large numbers of cars which show minimal center plate wear, and which did not require center plate repairs. Our Service Engineering Department has estimated the time required for typical repair procedures, and AAR Labor and Material charges are used. The life of the ASF proprietary Ride Control Truck may range from 750,000 to 1,000,000 miles depending on the type of service. We will use 800,000 miles for this example. We should emphasize, this life cycle analysis relates only to the ASF Ride Control Truck. Other trucks may exhibit different lives, and that life cycle data is proprietary to the designers.

Estimated time to jack a car, remove and disassemble trucks	1-1/2 hours
--	-------------

Repair 4 side frames including appli- cation of pedestal liners, rebuilding columns and application of new friction plates	3 hours
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Repair 2 bolsters including rebuilding the friction shoe pockets and gibs	7 hours
Repair of bolster center plates by reapplying liners	1/2 hours
	<hr/> 12 hours

AAR labor rate = \$16.77 per hour from Interchange Rules

$$\$16.77 \times 12 = \$201.24$$

AAR materials charges from Interchange Rules

Carset of Ride Control Shoes =	122.32
	<hr/> \$323.56

(Car mileage per year can range from 20,000 miles to over 100,000 miles; therefore, it is more meaningful to use dollars/mile for life cycle values).

$$\text{Life cycle cost of wear} = \frac{\$324}{800,000} \text{ mile} = .00041 \text{ dollars per mile.}$$

This is 0.04 ¢ per mile.

Some trucks do not have the wear protection afforded by center plate liners, and the early designs did not allow for their application. These tended to wear at greater rates and required rebuilding by weld procedures. A life cycle example for 200,000 mile maintenance is as follows:

Estimated time to jack car and remove trucks	3/4 hours
---	-----------

Rebuild center plates by welding and machining with proper equipment	4 hours
	<hr/> 4-3/4 hours

AAR labor rate = \$16.77 per hour	
\$16.77 x 4.75 =	\$79.66

Life cycle cost of wear for center plate repairs at 200,000 miles

$$\frac{\$80}{200,000} = .0004 \text{ dollars/mile or } 0.04 \text{ ¢ per mile}$$

It is our design practice to provide the maximum possible wear protection at each interface previously described. Also, we offer a premium suspension system with superior performance characteristics compared to the industry standard suspension. It offers stability to truck hunting and car body sock, and a greater reserve capacity in the suspension. This system (truck) was developed by laboratory and service testing procedures and offers various degrees of reduced wear and life improvement to both the truck and its environment depending on the service in which it is operated.

The effectiveness of the industry's and individual manufacturer's effort to optimize the life of truck components can be judged by some of the published figures. Mr. R.J. Ruprecht, in his paper on Freight Car Maintenance presented at the 11th Annual FRA Railroad Conference, 1974, indicated that the cost of repair materials in 1974 was approximately \$450 million (1974 dollars). \$35 million of this was for repair materials for freight trucks, and this included repairs for accidents, abuse and rebuilding programs. Thus, the primary load-carrying member of the freight car required less than 8% of the freight car maintenance dollars and approximately 1.3% of the total cost of 2.8 billion dollars for maintenance of equipment (not including maintenance of way) for Class 1 railroads as reported in the Yearbook of Railroad Facts, 1975 edition.

As a final note, it is appropriate to mention that the specialty Railroad casting industry contributes to the conservation of resources in the manufacturing process. Because electric furnaces require a near total charge of scrap as opposed to raw materials, the product is 99% recycled.

10. "The Analytical Wear Environment in the Railroad Industry"

There should be no doubt that component wear is an important consideration in the railroad industry. Approximately 750,000 worn freight wheels were replaced last year at a cost of nearly \$140 million. In a like manner the industry spent over \$250 million in 1974 on more than one million tons of new rail, the bulk of which replaced worn rail. Other speakers today will confirm that wear is the life limiting process in other important railroad components. In view of the financial straits of North American railroads, it would appear that wear rate improvements represent a potentially significant addition to railroad profits.

The industry literature has recognized the significance of wear since railroading began. In fact there seems almost a cyclic interest in wear and other problems as the intensity of railroad service has escalated at irregular intervals over the last 100 years.

A possible explanation for the absence of a comprehensive analysis of railroad wear may lie in a tendency toward "crisis research" within the industry. A good example of crisis is a rash of component related derailments. Such a circumstance is certain to release the creative energies of all concerned organizations. Rail and other types of wear are so commonplace that their economic implications are seldom considered within a crisis framework.

The preceding is somewhat more understandable with the realization that railroad operating personnel are totally dedicated to maintaining day to day railroad operations. Service irregularities are common enough to occupy their complete attention. Their awareness of the wear problem often surfaces as reactions to budgetary items as they inhibit or promote proper system maintenance. Their solutions to wear problems appeal to engineering first principles and common sense. Real time to such people is "right now", or highly compressed relative to other groups concerned with railroad wear problems.

Other groups called upon to address the railroad wear problem are the engineering and research staffs of railroad, supplier and contract research organizations. Their approach to wear problems are often oriented toward modeling of the system according to principles of mechanics, dynamics and material behavior. Their efforts are time consuming and their solutions often require system changes which might require twenty or more years to fully implement. For this reason, their solutions fall beyond the reference time frame for many railroad operating personnel.

An immense block in the path of railroad wear analysis is that known wear mechanisms do not appear immediately applicable to railroad problems. More factually, and for whatever reasons, those competent parties in the scientific and academic communities have not recently been engaged in efforts to structure railroad wear within a mechanistic framework. With apologies to those researchers whose work remains unknown to us, we are aware of only two university programs which address railroad wear problems. This is in marked contrast to practices of forty or more years ago when many universities were continuously engaged in railroad research.

Referring again to relative time reference frames of various parties, it hardly seems necessary to comment on the difference in this regard between academia and railroad operating personnel. One might ask what would comprise the necessary elements of a comprehensive railroad component wear program. The following which are extracted from the Track Train Dynamics Abrasion and Wear Program represent the collective effort of several individuals, some of whom are present here today. TTD has elected to initially focus on wheel, rail and truck centerplate wear with the expectation that the selected research format will provide adequate and complementary for investigations of other component wear problems. Highlights of this program are as follows:

a. Problem Identification

Any railroad system may be considered as a gigantic wear machine which depends on friction effects for any operation whatsoever. Friction at the wheel-rail interface provides tractive forces in response to control of train speed along the rail and to complex car structure interactions. Truck swivel and hunting are moderated in part by friction in the truck centerplate area. Friction snubbers are employed to control undesirable modes of system dynamics in freight car trucks. The wheel tread surface is employed as a brake drum in controlling train speed.

All such events are essential to train operation and contribute significantly to component wear. There are other friction events, however, which are necessary consequences of the physical system, yet are dysfunctional with regard to moving freight safely. Truck hunting is clearly dysfunctional as are certain modes of wheel-rail rubbing. The smaller part of problem identification is selection of components for study. There is a clear need to identify functional and dysfunctional components interactions as they contribute to wear. It is only in this manner that component redesign or material changes can be rationally approached.

b. Characterization of the Wear Environment

It follows from the above that an important goal of any wear program would be to identify component interactions and detailed causes as they contribute to wear. This task will certainly involve close inspection of worn components for evidence of plastic strain, metal loss and for identification of those wear modes which are operative. Also necessary is an evaluation of the physical system for information regarding the pertinent load and stress spectra as well as identification of rolling and rubbing elements of component motions. In other words, all system factors which contribute to component wear must be identified and, if possible, quantified.

c. Cost Effectiveness

It sometimes happens that a technically superior product fails in the marketplace. For this reason an effort must be made to express the use costs associated with existing components not only with regard to wear but with other aspects as well. The economic framework which evolves from this study will allow evaluation of proposed changes to the existing system. A straight forward example of such a circumstance is whether the higher cost of alloy or heat treated rail is justified by an expected increase in service life.

d. Laboratory Studies, Wear Mechanisms

The role of laboratory tests in this program will be to duplicate selective portions of the service wear environment while comparing material behavior in the laboratory to wear behavior observed in service. Such observations or patterns will then be gaged according to their adherence to a number of candidate wear mechanisms. It is desirable that the appropriate wear mechanisms be quickly identified so that program efforts will be expended in exercising the mechanism to resolve real world issues rather than vice versa. Another aspect of the laboratory studies will be the definition of those material properties which most directly influence component wear. In this manner the amelioration of component wear by optimum alloy selection may be achieved.

e. Wear Models

Most wear mechanisms are too highly specialized to apply directly to many railroad wear problems. For example, rail wear involves complex combinations of rolling and sliding contacts which induce metal loss and gross plastic flow. A wear model of the rail wear process will probably include a composite of two or more wear mechanisms.

f. Service Inputs

It is desirable that model builders and proposers of mechanisms be required to periodically touch base with the real world. For this reason, it is anticipated that railroad personnel with operating experience will be invited to support this effort in an advisory capacity. Similarly, the predictive capabilities of models and mechanisms will be evaluated with respect to service wear data such as will be generated in the IFAST program.

g. Mechanics and Materials

The wear issue involves material behavior under tractive contact stresses. TTD-II recognizes that resolution of these issues will require a multidisciplinary technical assault on the problem and will so structure the experimental team.

h. Predictive Wear Models - The Feedforward Factor

The availability of validated wear models and the identification of appropriate wear mechanisms will allow the following:

- The costs of dysfunctional wear may be evaluated and judgements may be made regarding acceptable solution costs.
- Wear rates estimates for conceptual component designs and non-standard alloy systems may be based on laboratory experience. The design and testing of non-standard component systems represents the major task of TTD Phase III commencing in 1978.
- The role of wear may be evaluated relative to all other factors which significantly affect component performance.

11. "Wear at the Wheel Rail Interface"

Today I wish to discuss the wear problems that exist at the wheel rail interface as a railway vehicle travels around a curve. While this may appear to be unduly restrictive, it should be remembered that wheel and rail wear are major expense items in railway operations. My remarks will be generally confined to Canadian National's experience on our Mountain Region because I am presently engaged in a major study of the cost of operating heavy vehicles over this portion of our main line. However, the data which I shall discuss today has very broad application, not only in Canada and United States but elsewhere in the world, wherever similar conditions exist.

About 1967 Canadian National began to use 100-ton vehicles to haul coal, potash, and sulphur in unit trains from the resource areas in Saskatchewan and Alberta to the Port of Vancouver in British Columbia. Coincident with introduction of these services, a program was initiated to replace the existing 100-pound rail with heavier 132-pound rail on the British Columbia portion of our main line. This portion of our main line has many sharp curves, as shown in Table XI-1.

It soon became apparent that rather severe rail wear was occurring particularly on the sharper curves, that is those of 4 degrees and above. In some extreme cases, the new 132-pound rail had to be removed in about one and a half years, the equivalent of about 40 million gross tons of traffic.

TABLE XI-1. RAIL CURVATURE DATA

<u>Degree of Curvature</u>	<u>Miles of Curvature in Track</u>	<u>Per cent</u>
0	293.76	57.4
1	27.55	5.4
2	35.96	7.0
3	31.33	6.0
4	40.92	8.0
5	18.81	3.7
6	35.59	7.0
7	7.71	1.5
8	<u>20.45</u>	<u>4.0</u>
Total	512.00	100.0

The rail wear problem is essentially one of extremely short life in curves and takes three forms.

- Gauge face wear on the high rail (See Figure XI-4)
- Head flow on the low rail (See Figure XI-5)
- Corrugations of wave length 8 to 30 inches on the low rail (See Figure XI-6)

A test was carried out in 1974 which established that the major cause of this excessive rail wear was the operation of fully loaded 100-ton vehicles in unit trains. The details of this test are fully explained in a Canadian National report entitled "Tests on B. C. South Line" and summarized in a paper given at the 1975 F. R. A. Conference at Pueblo, Colorado. Time does not permit much discussion of this work, however, three main points were stressed:

- (a) The gauge face wear was caused by vehicle tracking problems.
- (b) The head flow results from excessive contact pressure developed by the reverse curvature on the tread of worn wheels.

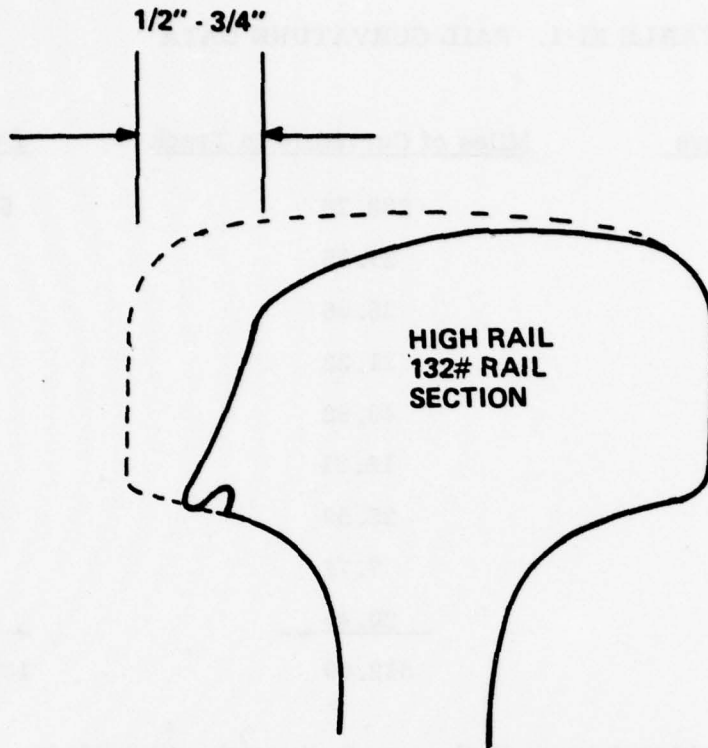


Figure XI-4. Gauge Face Wear on the High Rail

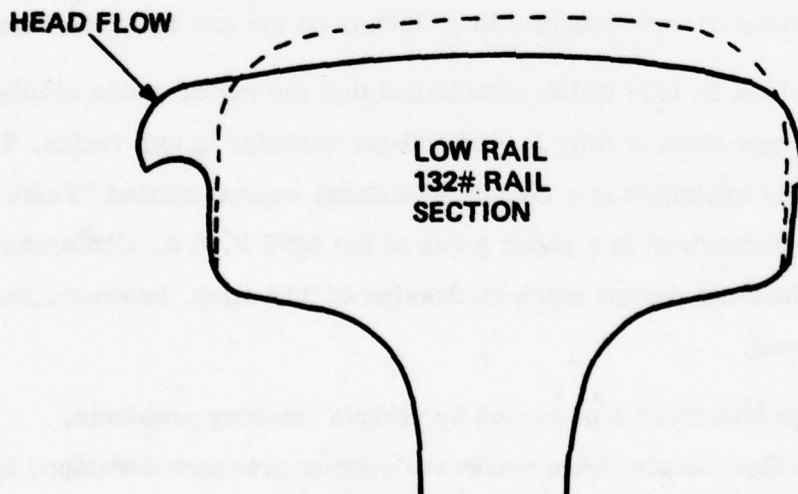


Figure XI-5. Head Flow on the Low Rail

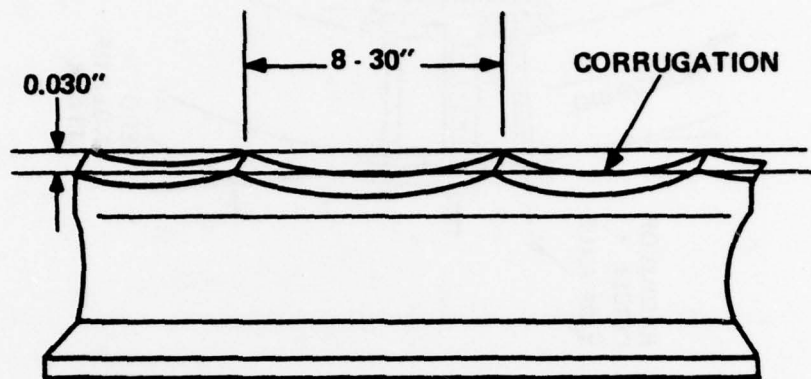


Figure XI-6. Corrugations of Wave Length 8 to 30 Inches on the Low Rail

- (c) The formation of corrugations appears to arise from a combination of conditions involving vibration of the vehicle and track structure, tie founding, rail lubrication, etc. However, the corrugations were associated with the excessive head flow condition of the rail. If the head flow could be prevented, it is believed that the corrugation problem would disappear.

What can be done to minimize or eliminate this problem?

The standard AAR new wheel profile has insufficient conicity to steer a wheel set around curves of greater than 2.4 degrees. In addition, the standard three-piece freight car trucks have sufficient clearances to allow the side frames to lozenge during curve negotiation, with the result that the flange of the wheel strikes the side of the rail with an angle of attack shown on Figure XI-7. This figure shows that even if there were no clearances, the flange of the wheel would still strike the rail at an angle. With heavy vehicles, a high lateral force is generated against the side of the rail and an abrading or scrubbing action occurs. What is required is a truck which would allow

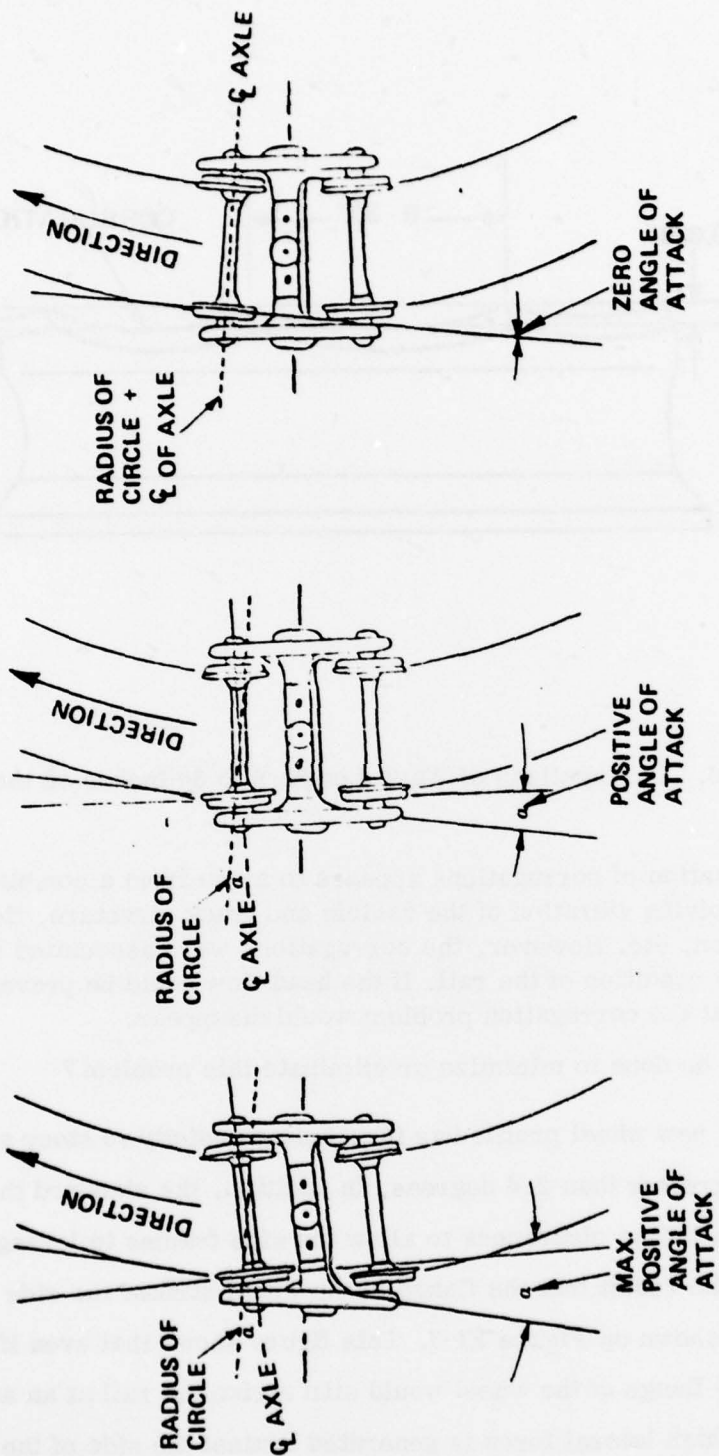


Figure XI-7. Angle of Attack of Leading Wheel in Curves

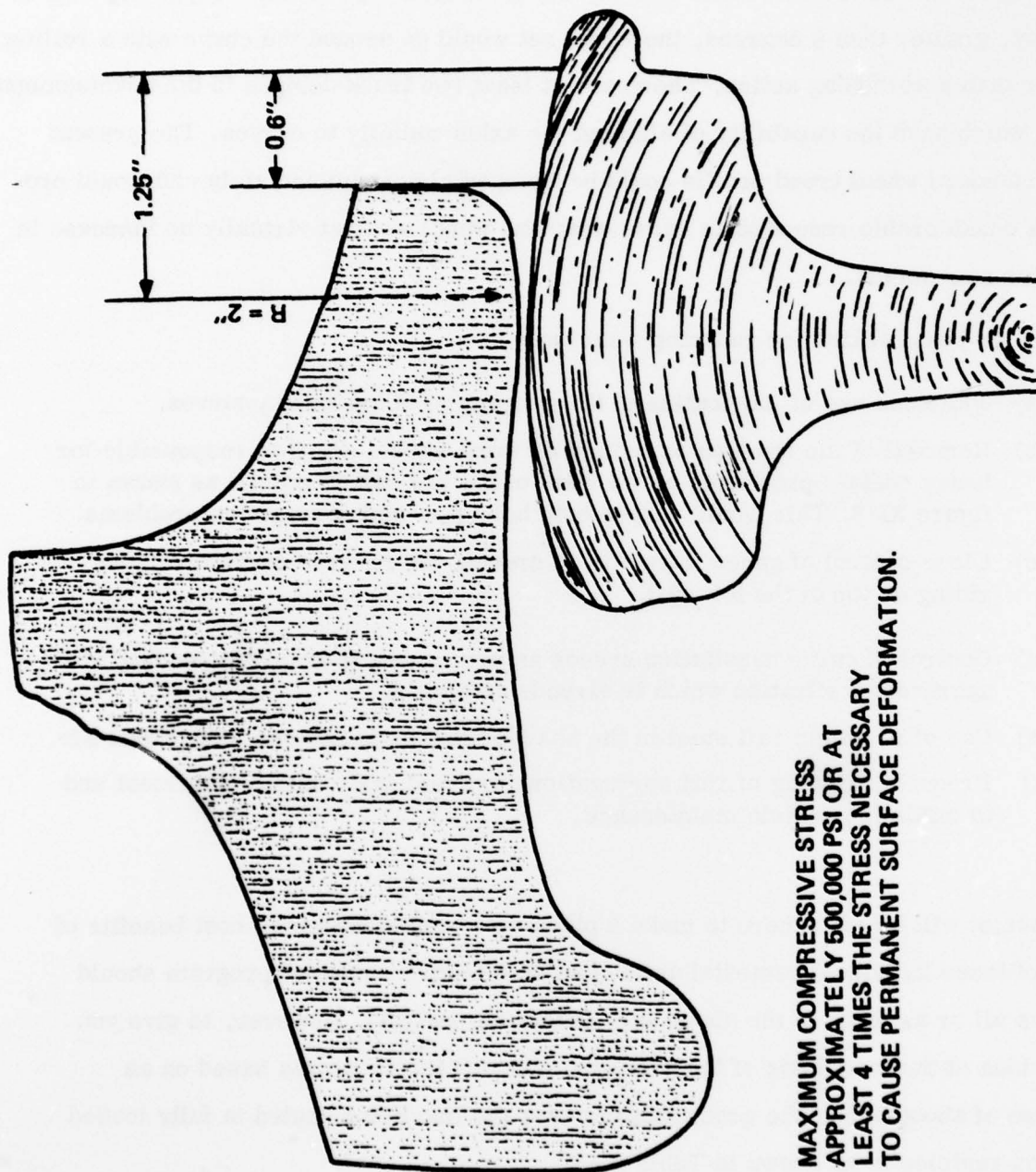
the axles to align themselves radially in the curve. Then if a wheel tread profile of sufficient conicity can be provided, the wheel set could negotiate the curve without flanging. Even if sufficient tread conicity cannot be provided for the very sharp curves of, say, greater than 6 degrees, the wheel set would go around the curve with a rolling rather than a scrubbing action. There are at least two truck designs in the developmental stage which have the capability of aligning the axles radially in curves. The present AAR standard wheel tread profile could be changed almost immediately and would provide a considerable reduction in curve wear and wheel wear at virtually no increase in cost for new wheels.

Other possibilities for reducing wear are: -

- (a) Judicious use of lubrication of the gauge face of the rail in curves.
- (b) Removal of the reverse curvature on worn wheels which is responsible for heavy contact pressures on the head of the low rail in curves as shown in figure XI-8. This would reduce both head flow and corrugation problems.
- (c) Close control of gauge in curves to prevent the reverse curvature from riding on top of the low rail.
- (d) Control of curve negotiation speeds as overspeeding or underspeeding will aggravate a situation which is already untenable.
- (e) Use of premium rail steel in the sharper curves to achieve longer rail life.
- (f) Frequent grinding of rail corrugations to avoid early rail replacement and to minimize vehicle maintenance.

No attempt will be made here to make a piecemeal breakdown of the cost benefits of each of these individual remedial actions as an effective remedial program should involve all or as many of the above suggestions as possible. However, to give you some idea of the magnitude of the problem, our rail life in curves based on an average of about 22% of the gross tonnage over the line being hauled in fully loaded 100-ton vehicles is as shown in Table XI-2.

It is apparent that the wear in curves of 4 degrees and greater is about four times that for tangent track. Based on this table, and an assumed replacement cost



MAXIMUM COMPRESSIVE STRESS
APPROXIMATELY 500,000 PSI OR AT
LEAST 4 TIMES THE STRESS NECESSARY
TO CAUSE PERMANENT SURFACE DEFORMATION.

Figure XI-8. Contact Between Wheel and Rail in Curves

TABLE XI-2. RAIL LIFE IN CURVES BASED ON 220 GROSS TONS IN FULLY LOADED 100-TON VEHICLES

<u>Curvature Degrees</u>	<u>Rail Life Million Gross Tons</u>	<u>Amount of Installed Curvature</u>
0	550	57.4
1	495	5.4
2	319	7.0
3	235	6.0
4	124	8.0
5	122	3.7
6	124	7.0
7	126	1.5
8	120	<u>4.0</u>
		100.0

of \$100,000 per mile of track, an estimate can be made of the potential savings possible if rail wear problems in curves can be reduced to the same level as exists for tangent track. For the conditions stated, that is the estimated rail life by degree of curvature and the percentage of curvature given in the table, there is an estimated saving of \$175 per mile of track per million gross tons over the line. For a line 500 miles long carrying 30 million gross tons annually, the saving amounts to 2.6 million dollars.

Many lines in the United States are now seeing an increasing tonnage carried in fully loaded 100-ton vehicles. If these vehicles run on lines with a large percentage of sharp curvatures, punitive rail wear of the magnitude stated above is likely to occur. This must be taken into account in costing new movements as system average costs are far from adequate.

Since the majority of new vehicles purchased for hauling bulk commodities have been 100-ton vehicles, a sharp increase in rail wear rates can be expected in curvy territory.

The situation with regard to wheel wear is more difficult to evaluate. However, based on actual wheel life data, two-wear wheels might be expected to last 340,000 miles. The wheels may be removed for condemnable defects such as tread wear, flange wear, skid flats, shelling, etc. Excluding the non-wear defects, the wheel sets will be removed for wear at about 180,000 miles, the wheel treads machined to a new profile, and the wheel sets replaced for an additional 160,000 miles' service. The wheel may then be condemned for either tread wear or flange wear. Even when the wheel is replaced for tread wear, the amount of flange wear present will affect the wheel life since on the first turning, additional tread material must be removed to restore the original wheel contour as shown in Figure XI-9. If the flange wear were not present, it is estimated that the existing rail life could potentially be increased by one-third, or 110,000 miles. At an estimated replacement cost of \$2,000 per car set, excluding axles and bearings, but including labour for removal and re-turning of the treads, this will work out to a saving of \$18 per million gross ton miles.

This is equivalent to \$18 per million gross tons over a mile of track.

This compares with a saving in rail wear of \$175 per million gross tons per mile of track, a ratio of almost 10 to 1. The cost of money is neglected in both cases as the annual cost depends on the density of traffic over the line, the utilization of the vehicles, and the length of haul.

It is obvious that the owner of the rail in track has a much greater stake in the development of a vehicle with improved curving properties than the car owner or the leasing company. Yet it is the car owner or lessor who will normally select the vehicle to be used. If optimum use is to be made of material, the material selection must be made on a system basis rather than on a component basis.

12. "Wear and Fatigue in Tapered Roller Bearings and Related Parts"
By Dr. W.E. Littmann

a. Material and Economic Cost of Wear and Fatigue.

At the present time it is estimated that between 1 and 1.8 million freight cars are in service in the United States and Canada. Among these approximately 800,000 cars

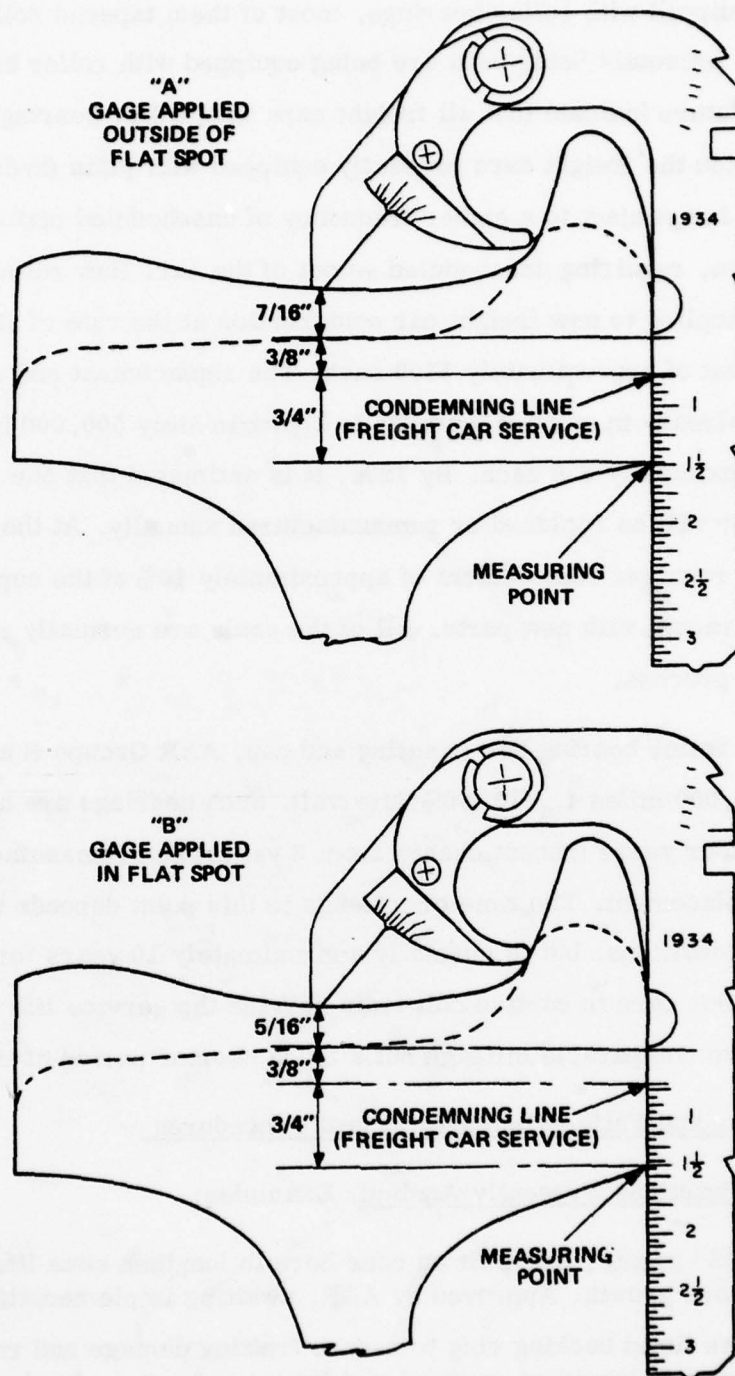


Figure XI-9. Method of Applying A. A. R. Steel Wheel Gage to Measure Amount of Metal to be Turned off Tread to Remove Flat Spot and also, Extra Metal to be Turned off to Restore Flange Contour.

are presently equipped with roller bearings, most of them tapered roller bearings. All new freight cars presently being built are being equipped with roller bearings and projections for the future indicate that all freight cars with roller bearings will ultimately replace by attrition the freight cars presently equipped with plain (hydro-dynamic) bearings, which are subject to a higher frequency of unscheduled maintenance or lubrication failure, requiring unscheduled setout of the car. New roller bearings are presently being applied to new freight car construction at the rate of about 500,000 per year, at a cost of approximately \$100 each. The replacement and remanufacture of roller bearings already in service amounts to approximately 500,000 bearings per year at a cost of approximately \$30 each. By 1990, it is estimated that one million roller bearings per year will be replaced or remanufactured annually. At the present time remanufacturing requires replacement of approximately 10% of the cups and cones (outer and inner races) with new parts. All of the seals are normally replaced in the remanufacturing process.

The present roller bearing has (rotating end cap, AAR Groups B and C) an estimated life of 500,000 miles $L_B - 10$ (90% survival). Such bearings are normally relubricated after four years (recent change from 3 years) and remanufactured at the time of wheel replacement. The time or mileage to this point depends upon wheel life and service conditions, but is normally approximately 10 years for cars in interchange service. For cars in captive unit train service the service life to wheel replacement would involve comparable mileage but a much shorter period of time.

b. Optimum Wear and Fatigue Damage Control Procedures

(1) Design Practices Presently Applied. Examples:

- .0005" greater press fit on cone bore to lengthen cone life as limited by bore growth. Approved by AAR, awaiting implementation.
- Press fitted backing ring to reduce fretting damage and resulting leakage of lubricant (grease) and ingress of water. Implementation is underway where needed. (Standard now on class Fund 6).
- "NFL" (No Field Lubrication) bearing designed to require no lubrication in the field until wheel replacement. Rubber rings around the cap screws to stop grease leakage. (Included in NFL) Approved by AAR, awaiting implementation.

- Lance type locking plate to prevent loosening of cap screws, resulting leakage of grease and loss of bearing adjustment.

(2) Design Practices Not Yet Generally Applied.

- Extended Performance Bearing (AAR Group B-1). This extended performance freight car tapered roller bearing introduced many of the design features currently incorporated in the "NFL" bearing, e. g. new grease specification, caulking around the backing ring, and no end cap lube fitting. In addition, the Timken "XP" bearing incorporates improved material and surface texture. The fatigue life is several times that of the standard AP bearing. The "XP" bearing should require no maintenance for a period of 600,000 miles or 10 years.

(3) Maintenance Procedures Presently Applied.

- Remanufacture at less than 1/3 the cost of a new bearing. Re-use of 90% of original bearing components.

(4) Maintenance Procedures Not Adequately Applied.

- Some railroad shops provide poor inspection, maintenance, and repair, e. g. failure to replace worn adapters. Various reasons can be stated, sometimes because none are available.
- Over-lubrication, leading to generation of excessive heat and false "hot box" indications with resulting unscheduled setout of the car, or breakdown of grease and subsequent leakage.

c. Optimum Procedures to Minimize Wear and Fatigue Damage not Generally Applied.

- (1) The "XP" bearing would permit remounting of the bearing without remanufacture at the first wheel replacement possibly more than one (or captive unit train service), but must be sold at a significant premium price.
- (2) Hardening of the adapter crown and shoulder areas would provide two to three times the life of unhardened adapters, but at a higher cost. Some users do not accept the fact that higher hardness on one surface increases the wear life of both mating surfaces.
- (3) Use of a hardened liner in the roof of the pedestal of the side frame (welded into place) can provide longer life and such a liner is easily replaced. The results would be substantially longer life for the side frames.
- (4) Heat treatment of wheels to increase wear life would also extend the service life before bearing remanufacture is required.
- (5) Improved truck design. Results from AAR Railroad Progress Institute FRA program on track train dynamics. Tests of new design are underway. For interchange freight car service, the added cost of the above is apparently not adequately reflected in the higher per diem rate to justify the higher

investment for the car owner. In captive unit train service, the return on the incremental investment can be more surely obtained, and the above measures are often applied.

It appears that the above improvements could be applied with a probable net decrease in overall costs. The related materials savings can be computed from the following figures: A typical new AP class F bearing weighs 109 pounds and includes 1.75 pounds of grease. In the remanufacturing process, approximately 10% of the steel parts are replaced (1 cup, 2 cones with rollers and cage plus the backing ring, total weight approximately 80 pounds). The steel involved in these parts contains approximately 3% total alloy, including principally Manganese, Nickel, Chromium and Molybdenum.

While the writer has no direct information on this project, it is unlikely that life-cycling costing is used for railroad rolling stock products, except possibly for unit trains and trailer train equipment.

While the Railroad Industry as a whole may not have a formally established wear control/reduction and cost program, it appears that the normal forces acting within the free enterprise system have created a continuing program of materials conservation and reduction of those costs directly related to wear and fatigue damage in railroad bearings. By means of vendor recommendations to the American Association of Railroads, friction and wear technology has been affectively applied to reduce the cost of railroad operation directly and indirectly related to railroad bearings. The change over from plain bearings to roller bearings which is now well underway, and should be complete by 1990, has taken place in response to such economic incentives as reduced frequency of lubrication failure in plain bearings and the associated costs of unscheduled maintenance, repair, and loss of car availability.* The vendors of roller bearings for railroad car applications in cooperation with AAR established the program for remanufacture of freight car roller bearings which was begun in 1969**. Many of

*Additional incentives were replacement of axles because of wear with plain bearings and ease of bearing replacement, when required.

**Begun in 1962 by the Timken Company with Trailer Train based upon earlier experience in repair of passenger car bearings.

the other improvements, above, have been achieved through recommendations by vendors and approvals by AAR. In those instances where a significantly higher cost must be incurred to obtain the net cost reduction, the owners and operators of railroad cars have performed value analyses in making their decision whether to adopt a given innovation or improvement. The vendors incentive, of course, is to offer an improved product in the hope of gaining a larger share of the total available market.

C. PARTICIPANTS/INVITEES AT SEMINAR #5

<u>Name</u>	<u>Affiliation</u>
E. Rabinowicz	Massachusetts Institute of Technology - Chairman
D. J. Albanese	Midland Ross (National Castings Div.)
R. Kaplan	OTA
J. Dahlman	Santa Fe
C. D. Dans	American Steel Foundries
M. Ephraim	General Motors
A. H. Hehn	GATX
J. Kalousek	Canadian Pacific RR
F. E. King	Canadian National RR
F. Korpics	Association of American Railroads
W. Kucera	Association of American Railroads
M. Lauriente	Department of Transportation
W. E. Littman	Timken Co.
G. C. Martin	Association of American Railroads
G. J. Moyar	Brenco Inc.
W. Pellini	Consultant
C. N. Rowe	Mobil Research
D. Stone	Association of American Railroads
T. Tallian	SKF Industries
V. Weiss	Syracuse University

CHAPTER XII

SEMINAR #6: CONSTRUCTION EQUIPMENT

A. MINUTES

It was decided by the participants of seminar #6 that they would unanimously accept the report submitted by their Chairman. * Due to this decision, no minutes were submitted for inclusion in the workshop proceedings.

B. TECHNICAL PAPERS PRESENTED AT SEMINAR #6

No formal technical papers were presented at seminar #6.

*The Chairman's Report for seminar #6 can be found in Chapter II, Section F.

C. PARTICIPANTS/INVITEES AT SEMINAR #6

<u>Name</u>	<u>Affiliation</u>
C. Kepner	Caterpillar Tractor Co. - Chairman
J. Garner	International Harvester
Bruce Kelley	Caterpillar Tractor Co.
A. Linville	Blue Grass Construction
W. Lux	J. Deere & Co.
Bob Meyer	Ho Penn Co.
R. Rogenmoser	Martin Tractor Co.
C. Sanders	Green Construction Co.
G. Thomas	F. J. Groves Co.
W. Winer	Georgia Institute of Technology